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AGARD LECTURE SERIES 193

Advanced Guidance and Control Aspects in Robotics

(La Perception de l'Environnement
par Senseurs Automatiques)

The material in this publication was assembled to support a Lecture Series under the sponsorship of the Guidance and Control Panel of AGARD and the Consultant and Exchange Programme of AGARD, presented on 6th–7th June 1994 in Lisbon, Portugal, 9th–10th June 1994 in Athens, Greece, and 21st–22nd June 1994 in Ontario, Canada.

NORTH ATLANTIC TREATY ORGANIZATION

Published June 1994

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North Atlantic Treaty Organization

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- Continuously stimulating advances in the aerospace sciences relevant to strengthening the common defence posture;
- Improving the co-operation among member nations in aerospace research and development;
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Abstract

To ensure the capability of defence, a demand for equipment and systems which can be embraced under the title of "Robotics" will emerge in the near future. In this context, "Robotics" represents a specific problem area involving all the guidance and control functions which are associated with achieving goal-oriented autonomous behaviour in structured and unstructured environments for mobile and manipulator systems as applied to ground, sea, air and space operations. Related robotic systems must combine constituent functions such as intelligent decision making, control, manipulation, motion, sensing and communication.

The scope of the special course will cover new developments in the areas of autonomous navigation for planetary and surface systems, and control and operations of remote manipulators.

Topics to be covered include:

- Kinematics, dynamics and mobility;
- Sensing (vision, tactile, acoustic, etc.) and sensory processing;
- Sensory interactive task decomposition, planning and problem solving;
- World modelling;
- Programming techniques and learning, cognitive control, adaptive sensory-motor control;
- System integration, test and evaluation;
- Man-machine interfaces.

Abrégé

Pour garantir les capacités de défense, un besoin urgent en équipements et systèmes qu'il convient de regrouper sous le vocable de "robotique" se fera sentir dans un futur proche.

Dans ce contexte, la robotique ouvre un domaine de problèmes spécifiques mettant en oeuvre toutes les fonctions de guidage et de pilotage qui sont associées au fonctionnement autonome sur objectif défini, dans des environnements structurés ou non, des systèmes mobiles ou des manipulateurs impliqués dans des opérations terrestres, maritimes, aériennes et spatiales.

Ces systèmes robotiques doivent combiner des fonctions composantes telles que le prise de décision intelligente, le pilotage, la manipulation, le mouvement, la détection et les communications.

Ce cours spécial présentera les nouveaux développements dans les domaines de la navigation autonome pour systèmes planétaires et terrestres ainsi que le pilotage et le fonctionnement des télémanipulateurs. Les sujets examinés comprennent:

- la cinématique, la dynamique et la mobilité;
- la détection (visuelle, tactile, acoustique etc.) et le traitement sensoriel;
- la décomposition des tâches sensorielles interactives, la planification et la résolution des problèmes;
- la modélisation du monde;
- les techniques de programmation et l'apprentissage, le contrôle cognitif, le contrôle sensoriel-moteur adaptatif
- l'intégration systèmes, les essais et l'évaluation
- les interfaces homme-machine.

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Robotics Technology Developments in the United States Space Telerobotics Program

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ABSTRACT

In the same way that the launch of Yuri Gagarin in April 1961 announced the beginning of human space flight, last year's flight of the German ROTEX robot flight experiment is heralding the start of a new era of space robotics. After a gap of twelve years since the introduction of a new capability in space remote manipulation, ROTEX is the first of at least ten new robotic systems and experiments which will fly before the year 2000.

As a result of redefining the development approach for space robotic systems, and capitalizing on opportunities associated with the assembly and maintenance of the Space Station, the space robotics community is preparing a whole new generation of operational robotic capabilities. Expanding on the capabilities of earlier manipulation systems such as the Viking and Surveyor soil scoops, the Russian Lunakhods, and the Shuttle Remote Manipulator System (RMS), these new space robots will augment astronaut on-orbit capabilities and extend virtual human presence to lunar and planetary surfaces.

BACKGROUND

During its history, NASA has undertaken a number of research programs aimed at developing remote manipulation capabilities for use in space. Extending back to 1961, these programs pursued the development of technologies for remote maniuplation with and without force feedback, coping with communication time delays, advanced system autonomy, advanced control techniques, free-flying and fixed base maniuplators, roving vehicles, intelligent mechanisms, operator interfaces, sensor components, control execution, perception systems, and mechatronics, among others.[1]

During this entire time NASA and the world-wide aerospace community gained very little experience in the operational use of robotic manipulation systems in extra-terrestrial environments. To date, there have been only four examples of a remotely manipulated device being used as an operational component of a spacecraft mission in an extra-terrestrial environment. This set is limited to:

- the Surveyor 3, 5, 6, and 7 missions, which soft-landed on the Lunar surface in 1967 and 1968. The Surveyors used a three-degree-of-freedom (DOF) soil scoop used to dig small trenches in the Lunar regolith in the immediate vicinity of the landing site. Samples from the trenches were then collected by the manipulator and placed

Presented at an AGARD Lecture Series on 'Advanced Guidance and Control Aspects in Robotics', June 1994.

onboard the spacecraft for analysis.

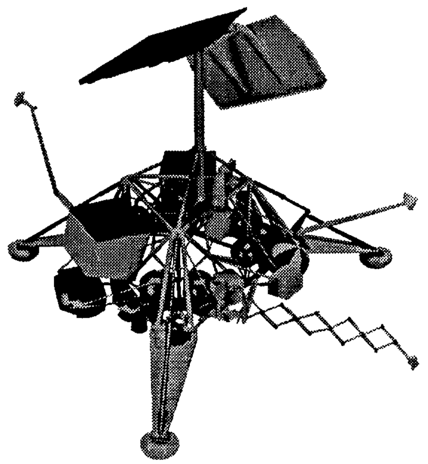

Figure 1: Surveyor spacecraft with deployed sampling manipulator

- the Viking 1 and Viking 2 missions which landed on Mars in July and September of 1976. The Viking landers included a four-DOF soil scoop used to collect Mars soil samples in the immediate vicinity of the spacecraft. Samples from the trenches were then collected by the manipulator and placed onboard for analysis.

- the Soviet Lunakhod missions, which sent two unmanned mobile wheeled rover vehicles to the Lunar surface. Each of these vehicles was operated by remote teleoperation without time-delay compensation. Navigation of the vehicles was performed via a observe-plan-transmit-move-wait strategy. Lunakhod 1 operated for approximately eleven Lunar days, traveling a total of 10 kilometers. Lunakhod 2, with twice the speed of Lunakhod 1 and more experienced controllers, traveled 35 kilometers in about five Lunar days. In addition to the teleoperated navigation capability, each Lunakhod also utilized a teleoperated point penetrometer which measured regolith densities.

- the current Space Shuttle Remote Manipulator System (RMS), which was first flown aboard STS-2 in 1981. This six-DOF manipulator is a 50-foot long, three-segment

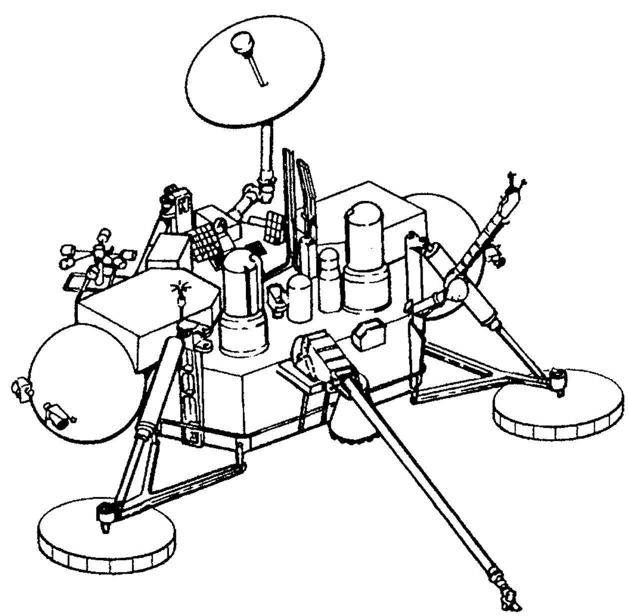

Figure 2: Viking spacecraft with deployed sampling manipulator

teleoperator with a snare-before-contact end-effector, and is designed for the deployment, capture and recovery of large Space Transportation System (STS) payloads. The RMS has been used to perform several tasks on-orbit, including the deployment of the Hubble Space Telescope (HST), use as an EVA astronaut foot restraint during the repair of Westar and Palapa-B, knocking ice from water dump nozzles on STS-41-D, and retrieval of the 21,300 pound Long Duration Exposure Facility (LDEF).

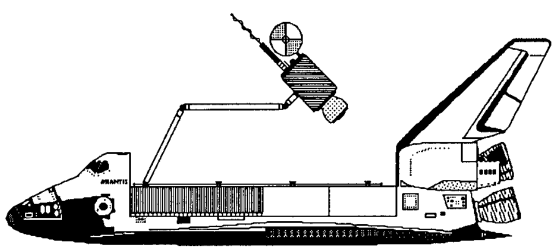

Figure 3: STS with the RMS deploying a payload

In all cases these devices are, by terrestrial standards, fairly primitive teleoperators with very limited capabilities. For example, terrestrial robots inherently have many capabilities which allow them to outperform humans on some tasks. They can be more precise and more repeatable and do not become tired or bored. Robots are chosen to accomplish tasks which are highly repetitive, which are very well defined, which exist in stable, unchanging environments, and do not require significant oversight or human intervention. Current terrestrial robotics can be characterized as:

- limited to industrial manufacturing
- preprogrammed control
- precisely structured environments
- single, highly repetitive tasks
- heavy, rigid devices

Teleoperators, with human controllers, have an advantage over robots in some other situations because of the difficulty of preprogramming reactions to all of the contingencies that may occur during a task. Current terrestrial teleoperation can be characterized as:

- limited to undersea and nuclear applications
- limited to real-time manual control
- used in semi-structured environments that are hostile to humans
- non-repetitive tasks
- limited maintainability and considerable backlash

Terrestrially, teleoperators are currently the choice for tasks which are not done sufficiently often to amortize the cost of programming a robot, tasks in which the environment cannot be sufficiently controlled to permit robot operation, tasks in which sufficient manual dexterity, sensing, and artificial intelligence is not yet available in robots, and tasks in which a human operator is warranted because of the cost of a possible failure of a robot is too high.

By comparison, space telerobotics technology requirements can be characterized by: [2]

- need for both manual and

automated control
- semi- to unstructured environments
- non-repetitive tasks
- variable time delay between operator and manipulator
- dexterous, lightweight and flexible manipulators
- complex kinematics and dynamics
- novel locomotion mechanisms
- minimal and simple servicing of the device
- hostile environment of thermal gradients, radiation, vacuum, variable lighting
- ability to recover from unplanned events, including system faults and errors

In short, the next generation of space telerobotics must be far more flexible than the current generations of terrestrial robots and teleoperators.

Biting Off Too Much

Historically, the space robotics community has been pursuing the goal of creating fully autonomous, self-contained robotic systems with considerable onboard intelligence as the next major objective in space robotics evolution. Systems such as the Flight Telerobotic Servicer (FTS) were intended to provide near-human levels of intelligence and dexterity, capable of interpreting very high level command structures and autonomously executing the commands without human intervention. Incomplete task operations, erroneous command structures, and reconciliation of differences between the world model and the real world were to be handled autonomously, and the entire system was to survive for up to 30 years on-orbit with little or no maintenance. The robot was designed to replace a full-time human operator with automated sensing, perception, planning and reasoning sufficient to conduct daily operations. The incentive was to remove the need for intensive human oversight of the robot's activities, and (anticipating that the human operator would be an on-orbit astronaut) thereby reduce the astronaut workload.

Since the initiation of the FTS and similar ambitious undertakings, the robotics community has gained new understanding of the research still required to create the technologies needed for such systems. While very significant progress has been made in supporting technologies such as system autonomy, task level controllers, control execution and robust operations, the day when all of these elements will come together into an operational autonomous space robot system is probably still a decade away (some roboticists have conjectured that it will not happen during their professional lifetimes).[3]

A New Focus

While the technology to support fully autonomous intelligent robotics is not yet available, operational needs for capable remote manipulation and locomotion still exist. To contend with these needs, the space robotics community has adopted a new approach which parallels that of the underwater robotics industry.

Until recently, deep subsea robotic operations were conducted with small manned submarines where the

operator had direct local control over manipulators physically attached to the sub. The operator's interface with the manipulators was limited, the workspace was cramped, and the environment was inherently dangerous. Recent advances in remote operation technology has permitted a shift in the operational paradigm, where manipulators are now carried on unmanned remotely operated vehicles (ROVs) which are controlled by remote operators safely and (relatively) comfortably located aboard a surface ship. Passing commands to the unmanned ROV via an umbilical, the operator utilizes an early version of telepresence technology to visualize the remote scene surrounding the ROV and control the manipulators.

In the space robotics arena, this same paradigm shift is taking place. Rather than attempting to force the use of immature technology to emulate the "smarts" of a local astronaut operator, the new focus is to utilize advanced teleoperation technology to move the operator from close proximity on-orbit to the ground. Technology elements including predictive displays, low-level reactive planners, sensor-based command execution and dynamic world modeling enable the ability to contend with problems associated with relocation of the operator, such as time-delayed communications, limited viewing options and limited command stream bandwidth. While there is still a long-term goal of developing intelligent autonomy for robots, the short-term goal has become the development of technology to push forward "intelligent teleoperation."

The major impact of this shift in development philosophy is the new opportunity to move robotics out of the laboratory and into the field. The maturation of advanced teleoperation technologies has helped increase confidence in the ability of robotic systems to robustly perform real tasks. With this increased confidence has come the acceptance of the potential benefits offered by space robotics technology, and the challenge to "fly it and prove it" with a series of robotic flight experiments and demonstrations. For the first time since the first flight of the Shuttle RMS, new operational robotic tools will be seen on-orbit and on planetary surfaces. And rather than waiting for more than a decade between the introductions of new robotic systems, the new push to "get things flying" will yield multiple new space robotic systems before the end of the 1990's.

The robotic systems to be flown during the next five years fall into three distinct categories: Extra-Vehicular Robotic (EVR) servicers, science payload servicers, and planetary surface rovers. Flight experiments, technology demonstrations and operational systems are being built in each of these categories by NASA, academic, industrial, and international developers.

EVR Servicers

The EVR servicer systems are robotic systems deployed in Earth orbit for use outside of pressurized, controlled environments. Such systems are typified by the Shuttle RMS, which was first flown on the STS-2 mission is 1981. Target applications for these systems include on-orbit satellite assembly, maintenance, repair and servicing, robotic enhancement of Shuttle payload bay operations, and ground-control robotic servicing of external Space Station payloads. Within the EVR

servicers class, six different efforts are currently underway, in Space Station- and Shuttle-attached as well as free-flying configurations.

Canada is providing two space robots for use on the International Space Station. The Space Station Remote Manipulator System (SSRMS) is a 55-foot long, 7-Degree Of Freedom (7-DOF) manipulator similar to the Shuttle RMS. Designed to maneuver and locate large payloads along the Space Station truss structure, the SSRMS can transfer power, data and video signals from attached payloads via the latching end effectors at both ends of the arm. These end effectors allow either end of the SSRMS to receive power and operate from any Power-Data Grapple Fixture on the Space Station. They also permit the SSRMS to change locations on the exterior of the Space Station by "inch-worming" from worksite to worksite.

The second Canadian system is the Special Purpose Dexterous Manipulator (SPDM), a dual-arm dexterous robotic system composed of two 7-DOF manipulators, a Power-Data Grapple Fixture, and supporting structures and tooling. The SPDM is controlled during teleoperations with two 3-DOF hand controllers and via keyboard entry and/or preprogrammed sequences for automated trajectory control. Each manipulator is controlled separately, in addition to independent control for the SPDM body and the SSRMS (during operations where the SPDM is positioned by the SSRMS). Human-in-the-loop and automated trajectory control modes are supported.[4]

At the same time, Japan is preparing a dual-manipulator system as an element of the Space Station Japanese Experiment Module (JEM). Composed of the Main Arm and Small Fine Arm, the JEM Remote Manipulator System (JEMRMS) is intended to provide maintenance, servicing and changeout of science packages placed on the JEM exposed experiment carrier. The Main Arm, similar in configuration to the SRMS and SSRMS, is a 6-DOF positioning tool used to transport large payloads and provide coarse positioning for smaller, more dexterous manipulators. The Small Fine Arm is a 6-DOF manipulator which can be operated either from the end of the Main Arm, or from a fixture on the exposed experiment facility. The JEMRMS can be controlled either with local teleoperation, or with position-based preprogrammed motions. The system will be launched on the same Space Station assembly flight as the JEM pressurized module, and then followed by the JEM exposed experiment facility which it will support.[5]

Under development by Martin-Marietta Corporation and the NASA Johnson Space Center, the Dexterous Orbiter Servicing System (DOSS) is being developed to provide dexterous manipulation capability for operations in the Space Shuttle payload bay. The DOSS utilizes the flight manipulator delivered by the OACT Flight Telerobotic Servicer (FTS) Technology Capture Program to provide dexterous manipulation capability for the STS Orbiter payload bay. It is the culminating element of a national investment of over $250M in dexterous space robotics development that spans eight years. The DOSS is an MPESS-mounted robot that can operate from a fixed base or from the end of the Remote Manipulator System (RMS). The purpose of this arm is to provide the crew and mission controllers with

an alternative to EVA for performing payload bay operations. These activities include EVA worksite setup, payload operations both nominal and contingency (e.g. subsystem deployments), and many Orbiter contingency operations (e.g. repairs). The DOSS is designed for repetitive flights and is intended to become a baseline capability for STS servicing operations and also function as a testbed for future telerobotic experiments. Simultaneously, the first DOSS flight experiment will be used to validate components and techniques to be used in the assembly and maintenance of the International Space Station Alpha (ISSA).

The first flight of the DOSS, currently scheduled for June 1996, will demonstrate and evaluate the performance of the dexterous robotics manipulator system in space through the performance of Space Station-type maintenance and servicing tasks. This will include the characterization and verification of the manipulator system in a micro-gravity, thermal/vacuum environment and demonstrate Space Station Technology Flight objectives while proximal to Russian MIR space station as part of the ISSA risk mitigation effort.

DOSS is central to two major flight proposals that are being pursued by the International Space Station Office: The DOSS Risk Mitigation Flight Experiment, and the American Fine Arm Operational Flight System. Both of these systems are built around the Flight Telerobotic System flight manipulator and the Hydraulic Manipulator Test Bed that were produced as a result of the OACT FTS Technology Capture Program. As of April 8, 1994, the Space Station Risk Mitigation Program has planned participation in the DOSS implementation, complimenting the OACT activity. The OSSI Hubble Space Telescope Servicing Program may participate in the project starting in FY 95 based on the results of their ongoing requirements analysis.

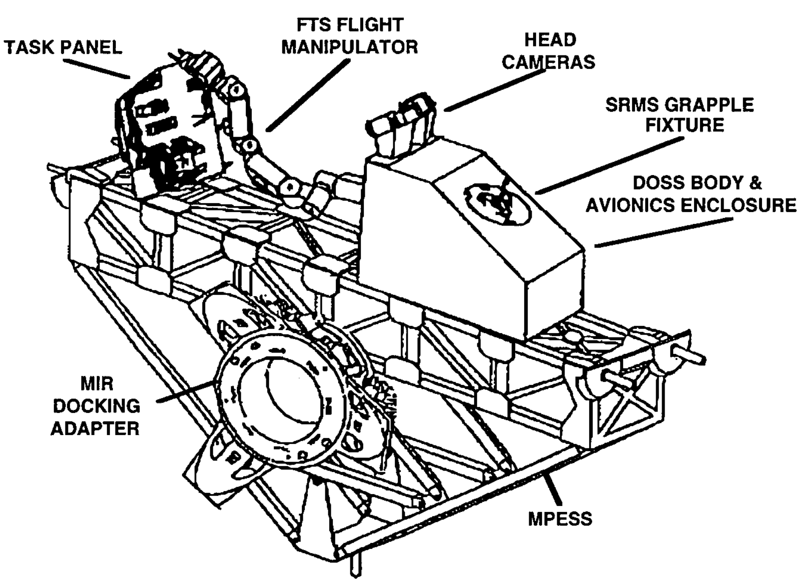

Figure 4: Potential configuration for the Dexterous Orbiter Servicing System flight experiment

The DOSS flight experiment will demonstrate technology and techniques which are required elements for the planned robotic assembly and maintenance operations for Space Station. The results of the DOSS flight experiment will directly impact the design, development and implementation

of the system which will provide dexterous robotic capabilities for ISSA, and offers the only opportunity to flight validate these technologies before the planned delivery of the operational system (either SPDM or AFA, described below).

Simultaneously, the OACT Telerobotics Program is currently negotiating with the Space Shuttle program office to determine the long-range plans for operational utilization of the DOSS following the flight experiment. Following the first flight in CY 1996, the project will transition the device over to the STS Operations community, where the DOSS will be integrated in as an operational element of the STS servicing toolkit. Ongoing operations, maintenance, and support costs will be provided by STS Operations and the user missions. These negotiations are not yet completed, but it is believed that the STS program office will be a full partner in the project once the current study is complete.

The Ranger project is being conducted at the University of Maryland, under sponsorship of the NASA Office of Advanced Concepts and Technology Telerobotics Program. Over the past decade, NASA has been actively researching telerobotics technology to facilitate future operations in space. The Ranger vehicle, shown here in a computer generated simulation, is designed to be the first low-cost flight experiment to extend these laboratory investigations to space flight experience. Ranger is a dual-arm free flying telerobotics flight experiment which will conduct on-orbit validation and verification of many of the technologies developed by the NASA program.[6]

To better understand the capabilities and limitations of current methods for simulating the space environment on Earth, two Ranger vehicles are being built. The first one is designed to operate underwater, and will be extensively tested at the Neutral Buoyancy Research Facility on the University of Maryland campus to get basic data on its' operations and capabilities. The second vehicle, as nearly identical to the first as practical, is currently scheduled for flight in late 1996 aboard an expendable launch vehicle. The project will correlate neutral buoyancy robotic simulations by developing nearly identical underwater and space flight units, and performing identical tasks in both environments.

On orbit, Ranger will demonstrate a variety of tasks necessary for future space operations, from the simple replacement of standard Orbital Replacement Unit (ORU) modules, to complex satellite servicing and refueling tasks which to date have only been performed by astronauts in space suits.

The project includes collaboration with the Jet Propulsion Laboratory, Langley Research Center, and the Michigan Space Automation and Robotics Center. It will carry experiments from every NASA center involved in the NASA Telerobotics Reserach Program, as well as experiments from industry and other universities. Utilizing telepresence ground-based control, coordinated manipulator operation, automated rendezvous and docking technology, and a hybrid propulsion system, Ranger will conduct a simulated satellite servicing exercise to characterize the operational capabilities of free-flying robotic systems.

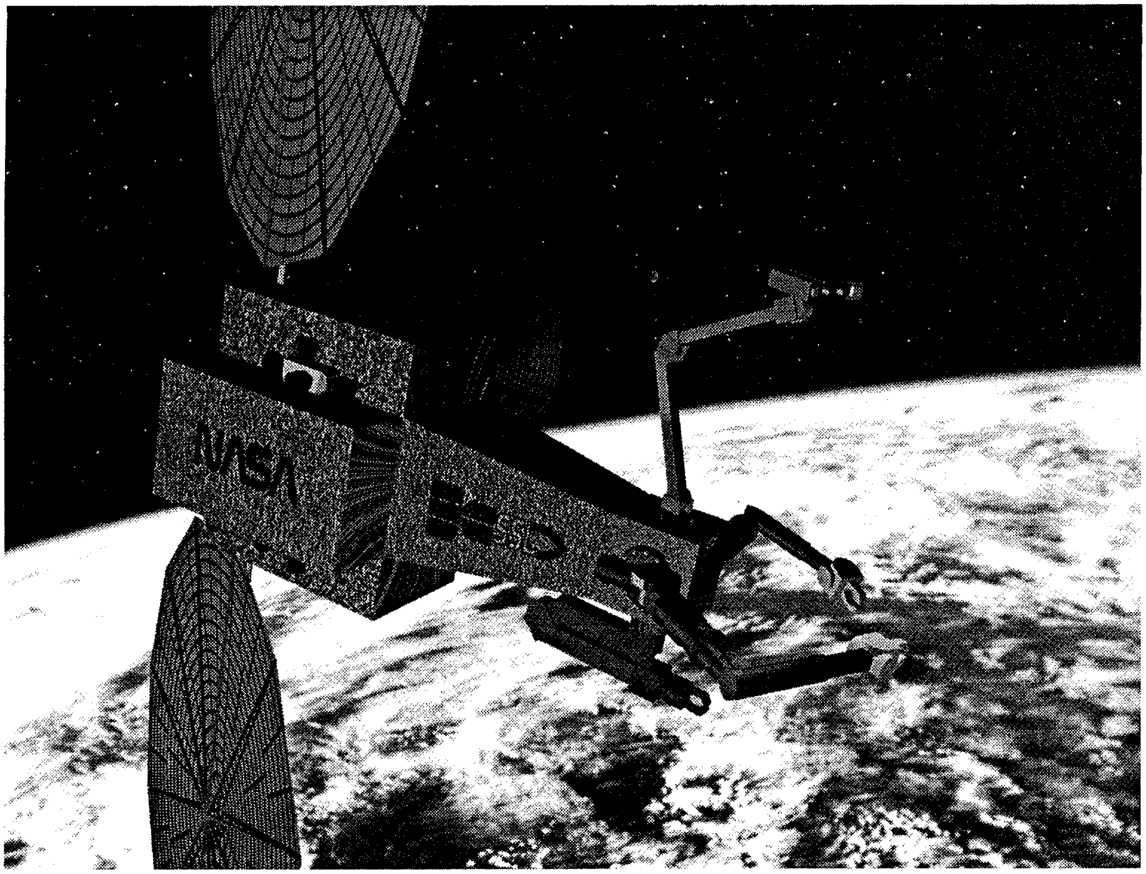

Figure 5: The Ranger telerobotic flight experiment

Utilizing telepresence ground-based control, coordinated manipulator operation, automated rendezvous and docking technology, and a hybrid propulsion system, Ranger will conduct a simulated satellite servicing exercise to characterize the operational capabilities of free-flying robotic systems. Development costs for the system are being reduced by making selective use of Class-S and Mil-Spec components, maximizing the use of commercial-quality components, maximizing in-house operations on the flight hardware, compressing the hardware development cycle by concurrent engineering of the neutral buoyancy and flight designs and using neutral buoyancy hardware to validate flight systems. Both Ranger vehicles will be designed as the first in what is hoped to be a long series of opportunities to augment technical education in the United States by encouraging direct student involvement in exciting, important space research. Ranger will represent a new class of low-cost expendable robots designed for research and servicing in areas beyond the reach of the Space Shuttle.[7]

Japan is also developing a free-flying robotic servicing experiment, scheduled for flight in 1997 aboard a H-II rocket. The National Space Development Agency of Japan (NASDA) and the Ministry of International Trade and Industry (MITI) are developing this experiment

to verify automated rendezvous and docking technologies. A target vehicle and chase vehicle will be deployed to exercise technologies including GPS receivers, rendezvous radar, proximity CCD sensors, docking mechanisms and onboard guidance computers. Simultaneously, a 6-DOF manipulator mounted on the chase vehicle will be used to demonstrate cooperative control of the chase vehicle attitude as it reacts to manipulator position, ground-based teleoperation of the manipulator, demonstration of on-orbit satellite servicing including fuel transfer and battery exchange, and target vehicle acquisition, grappling and restraint.[8] It is interesting to note that NASDA has publicly stated they consider it a matter of national pride that ETS-VII fly before the Ranger experiment, and are currently attempting to accelerate the implementation schedule to enable an earlier launch date.

Science Payload Servicing

Science payload servicing robotics differ from the EVR systems in that they are designed to maintain experiment payloads in controlled environments, and are specifically designed as elements of nominal experiment operations (ie. the robot is intended to be a functional component of the overall experiment, performing tasks such as reagent replenishment, product harvesting, sample collection, etc.), and not just as contingency and repair systems in the event of experiment failure or malfunction. The functions performed by the servicer are intended to off-load the requirements for intensive astronaut maintenance of these payloads, and permit operation of the payloads during periods when astronauts may not be present.

At least two such systems are currently in the final stages of preflight integration. McDonnell-Douglas has recently completed development of Charlotte, named for the fictional arachnid star of *Charlotte's Web*. Charlotte is a small (approximately two cubic feet) robot which is physically connected to it's work environment with a series of eight Kevlar strands. The strands extend from the corners of the robot's rectangular body to hard points at the extreme corners of the workspace, which may be the interior of SpaceLab, SpaceHab or a space station module. By increasing and releasing tension on selected strands, the body of the robot is able to translate throughout the entire volume of the workspace. Position accuracy and repeatability is surprising, and the device has no problem positioning it's manipulator to utilize the physical interfaces associated with the front-panel controls of most experiments. Charlotte is currently scheduled for flight on the SpaceHab-3 mission.

The Robotic Operated Materials Processing Systems (ROMPS) is a joint project between the NASA Goddard Space Flight Center, the Michigan Space Automation and Robotics Center, and the Zymark Corporation. The objective of ROMPS is to demonstrate lowered costs of on-orbit processing through the use of robotics to autonomously produce semi-conductor materials. Scheduled for launch on STS-64, this GAScan experiment will investigate zero-gravity annealing of semi-conductor thin films. Contained within the experiment canister will be a conventional terrestrial laboratory automation robot qualified for space use. This robot will utilize low-level automation to maintain the materials furnace, supply source substrates to

the furnace and harvest processed thin films. Specific issues overcome during the qualification of the terrestrial robot for use in the on-orbit materials processing facility include exclusion of hydrocarbon-based lubricants, use of low off-gassing materials, incorporation of low particulate-producing mechanisms, and integration of force sensing for reliable handling of fragile films.

It is also appropriate to mention that the European Space Agency is investigating the incorporation of a large-scale science payload maintenance robot system into the Columbus module of Space Station. This system would have a work envelope encompassing the entire interior of the module, and would provide logistics support for minimally-tended science experiments and materials production systems.

Planetary Surface Systems

Of the three classes of space robotic systems, planetary surface robotics is one in which is largest breadth of knowledge exists, although it is somewhat dated knowledge. As early as 1967, the Surveyor missions carried simple remotely-operated manipulators to the surface of the Moon to collect samples of the Lunar regolith. Followed by the Russian Lunakhods in 1969 and 1980, and the Viking missions to Mars in 1976, these early efforts identified the fundamental environmental constraints and technology obstacles to be surmounted to enable the development of robust, long-lived planetary surface robotics.

It was traditionally accepted that the next generation of robotic rovers for unmanned Lunar and Mars missions would be large (800-Kg or more), monolithic, highly intelligent and autonomous devices which would require significant development and operational support in terms of technology, budget, computational and human resources. Then in 1989, a small group of rogue technologists at MIT and JPL began an new initiative in micro-rover technology based on subsumption architectures. Making use of progressively smaller computers, increasingly advanced sensors, and maturing mobility systems, a series of micro-rover testbeds was developed which culminated in the MESUR (Mars Environmental Survey) Pathfinder Rover. This six-wheeled 5 Kg-class rover is scheduled for launch to Mars in 1996, and will perform technology validation experiments in addition to science investigations and instrument deployment. Control for the rover will be shared between Earth and the limited onboard intelligence of the rover. The Earth-bound operator will use camera views from the MESUR lander to designate major terrain features as navigation waypoints in the vicinity of the lander to be either avoided or visited by the rover. By combining sensory input with predefined "behaviors" the rover will autonomously navigate between the waypoints, avoiding rocks, crevasses and other impassable terrain. At the same time, the minimal onboard computational system will be working overtime to store, compress, packetize and transmit rover imagery and other telemetry back to the lander via UHF modem, where it is then relayed to Earth. To maintain an extremely low-cost funding profile (as compared with previous planned systems such as the Mars Rover Sample Return project), the rover design philosophy duplicates that of the Ranger project: extensive

use of commercial- and military-quality components, maintaining a small development team, rapid prototyping with concurrent engineering, streamlining of component procurement and qualification procedures, and intense industry involvement and buy-in.

Also scheduled for flight in 1996, Russia intends to launch the Mars '96 mission which will include the Marsokhod rover. Being developed by the Institute for Space Research (IKI) and the Babakin Center of NPO Lavochkin, the Marsokhod is a six-wheeled, 100-Kg rover will use radioisotopic thermal generators (RTG) for power generation and thermal control. Because of the RTGs, the rover will be able to operate during the Martian night, and is expected to have a long surface lifetime (one year or more) with a potential total excursion distance of over 100 kilometers. The Marsokhod enables exceptional mobility characteristics through the use of unique bi-conic titanium wheels and a segmented three-part chassis. IKI is currently discussing possible United States participation in the project, which would incorporate telepresence control technology developed by the NASA Ames Research Center and a lightweight 6-DOF manipulator system developed by McDonnell-Douglas into the flight system. Field tests of the Ames Virtual Environment Vehicle Interface (VEVI) have already been conducted with a prototype Marsokhod rover located on the Russian Kamchatka Peninsula, and the operators located in Huntington Beach, California.[9]

In addition to these Mars-bound rovers, LunaCorp, a Virginia-based corporation, has recently announced plans for a lunar rover project slated for launch in 1998. Rather than driven by science needs, the incentive for this project is primarily entertainment - the goal of the project is to provide the world's first interactive space exploration event by giving the public the opportunity to drive the rover on the moon. The rover will be remotely operated via telepresence control from workstations located in theme parks around the country. Funding for the project is to come from theme park operators, television networks, corporate sponsors and advertising agencies. Capitalizing on NASA rover technology developments, LunaCorp is working with Carnegie-Mellon University to transfer these technologies into the first commercial lunar rover application. The project will use a Russian Phobos launch system, purchased through International Space Enterprises, to deliver the

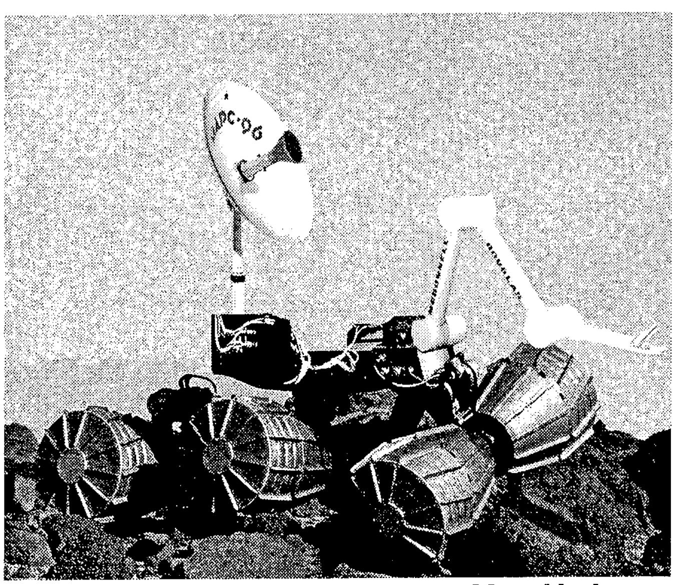

Figure 6: A prototype of the Russian Marsokhod rover undergoes terrestrial field tests in Death Valley

lander and rover to lunar orbit. Following descent and landing, the rover will initially explore in the vicinity of the Apollo 11 landing site, and then initiate a traverse across the Lunar surface of up to 1000 kilometers. A combination of predictive display, telepresence and virtual reality control systems will be used to compensate for the 4-8 second time delay associated with communicating across the Earth-Moon distances. Detailed virtual reality reconstructions of the regions explored by the rover will allow potential rover drivers to practice navigating the rover in simulation before they take over control of the real system. While most of the technology obstacles associated with this concept have already been addressed, the real hurdle will be the creation of appropriate system intelligence which can react in real time to prevent an operator from driving the rover into a system-fatal situation.

Terrestrial Technology Transfer

While the space applications development efforts continue as full pace, parallel efforts are being driven to force the new technologies developed by these efforts into terrestrial applicability. As each on-orbit robotic system moves closer to actual flight, by-products of the effort, such as fundamentally new robotic joint designs, exoskeleton systems, fundamental robotic control theory development, and widely-applicable proximity sensor technology are produced. Each of these component technologies hold the promise of improving terrestrial robotic systems for both space- and non-space related uses. The NASA robotics program provides a mechanism for the application of developed technologies into terrestrial task environments. These tasks move the technologies developed in the other elements of the program from the laboratory setting into operational use, and take advantage of the relatively easy terrestrial access, well understood environments, and myriad problems to be solved to demonstrate the applicability of space telerobotics.

Throughout the life of the NASA Telerobotics Program, NASA has worked to build and maintain coordination with other government robotics programs, including those of the National Science Foundation (NSF) and the National Institute of Standards and Technology (NIST). These efforts include cooperative activities, collaborative research, and external transfer of NASA-developed robotics technology. These efforts have three purposes: to develop industrial applications of telerobotics technology, to apply telerobotics technology to terrestrial science and research efforts,and to strengthen intra-government coordination. Several of the activities are summarized below, beginning with the efforts targeting development of industrial applications of telerobotics technology:[10]

- The Automated Manufacturing Research Program, conducted by NIST is investigating automation in factory-floor settings, and the relative advantages of improved work cells against more capable manipulation systems. NASA participates in the annual program review conducted by NIST, and coordinates with NIST to transfer NASA-developed robotics workcell technology into this effort.

- In previous years, NIST and the NASA telerobotics efforts have cooperatively developed several new technologies and architectures for the control of robotic systems. For example, the NASREM robot control architecture was jointly developed by NASA and NIST as a precursor to the NASA Flight Telerobotic Servicer program. The architecture is now used as a standard architecture definition methodology by many NASA, NIST and industry projects. NASA has directly supported NIST in several of these cooperative activities, with annual funding for robotics research reaching up to $1 million per year.

- The NASA and NSF robotics research programs have jointly co-sponsored the "Bilateral Exchanges on the Approaches to Robotics in the United States and Japan" conference, which conducted investigations into the methods, techniques and technologies used by government and industry to research and develop fundamental new robotics technologies. The outcome of this activity was publication of a manuscript which contrasted the approaches used in the United States and Japan, and which offered NASA and NSF insights into the content of the robotics development programs supported by MITI, NASDA, and several Japanese industries.

- The Advanced Research Projects Agency (ARPA) has selected the Langley Research Center robotics program as one of their technical agents in the area of robotics. Under this agreement, LaRC and DARPA cooperatively issue university research grants to sponsor the development of innovative new robotics technologies, as well as increase robotics educational expertise in the United States.

- The program has maintained close ties with the U. S. space robotics industrial community, and monitored industrial developments of potential applicability to the NASA space robotics and planetary rover research efforts. For example, the Martin-Marietta Corporation participates in the Telerobotics Intercenter Working Group, and in technical program reviews and assessments such as the Space Systems Technology Advisory Council. This coordination facilitates the transfer of NASA-developed technologies to the space robotics industry, and aids in the rapid application of these technologies to terrestrial manufacturing and automation problems.

- The program coordinates with several robotics industry advisory and technology interchange groups, to facilitate the transfer of NASA-developed technology to the industrial community and receive comments on the

overall direction and focus of the program. One such group is the Space Automation and Robotics Technical Committee (SARTC) of the American Institute of Aeronautics and Astronautics which meets three or four times annually with the charter of disseminating information about space automation and robotics and promoting the technology to industry, academia, and government. The SARTC is composed of industry representatives from the aerospace community, as well as government and academia.

Some of the efforts which target application of telerobotics technology to terrestrial science and industry efforts are listed below:

- Several programs sponsored by NSF both sponsor and utilize telerobotics and robotics technology research and development. In 1992 NASA and NSF cooperated in conducting the Mt. Erebus Explorer project, a project to deploy a robot into the interior of a volcano crater in the Antarctic. This project, conducted as part of the Telerobotics Program and the Antarctic Space Analog Program, demonstrated innovative new robotics technologies developed by NASA. It is anticipated that this project will spawn several new activities which may revolutionize volcanic sample collection and lead to significant new applications of robotics in terrestrial field science operations. This project is being continued with the United States Geological Survey, and will deploy the Dante robot to a volcano in Alaska in the summer of 1994.

- In addition to the involvement with the NSF Polar Programs Division (which cooperated with the Mt. Erebus Explorer project), NASA is currently negotiating with the NSF Oceans Division to investigate the potential for application of NASA-developed robotics technology to underwater science sampling operations. Of particular interest is the underwater Remotely Operated Vehicle (ROV) technology which NASA developed and demonstrated under the Antarctic sea ice with the cooperation of NSF in 1992. Additional negotiations are underway with the NSF Information, Robotics and Intelligent Systems Division to jointly sponsor robotics research and investigate opportunities for transfer of NASA-developed robotics technologies to NSF grantees and research programs.

- The robotics laboratories at the Jet Propulsion Laboratory have been working with Computer Motion, Inc. to develop technologies for applications where human ability to perform a task is limited by human dexterity and physical capabilities. One specific application has been in minimally invasive laproscopic surgery. This type of medical procedure makes

use of remote cameras, known as laproscopes, which are typically held by an assistant to the surgeon during a procedure. The assistant has control of the surgeons field of view, and the surgeons performance is often limited by the efficiency of communication with the assistant. To address this problem, the project has developed the Automated Endoscopic System for Optimal Positioning (AESOP), a robotic assistant which holds the laproscope and is guided by the surgeon with a foot- and/or hand-controlled interface. Thus the surgeon is able to gain control of the viewfield by direct coordination between himself and a robotic assistant.[11]

- JPL has also worked with Cybernet Systems Corporation to develop the PER-Force hand controller which manipulates robots or objects by "feel". this small backdrivable robot is combined with advanced machine vision processing and enhanced computer generated visual/tactile force feedback cues to enable an enhanced interface for the use on hazardous environment operations. This system has been implemented with a goal of integrating it within the manufacturing environment and tasks which have no immediate solution with hard automation or changes in methodology or workcell design. One example application being developed is pick-and-place operations for automobile transmission packing.[12]

- As an offshoot of work sponsored by the program, the Stanford University Aerospace Robotics Laboratory and Real-Time Innovations, Inc. have developed ControlShell, a next generation CASE framework for real-time system software development. ControlShell includes many system-building tools, including a graphical flow editor, a component data requirement editor, a state-machine editor, a distributed data flow manager, an execution configuration manager, an object database and a dynamic binding facility. ControlShell is being used in several applications, including the control of free-flying robots, underwater autonomous vehicles, and cooperating-arm robotic systems.[13]

- NASA has teamed up with Limbs of Love and a group of medical and prosthetics specialists, prosthetics users, insurance industry representatives, and university researchers to identify research objectives in prosthetic limbs. As part of this effort, the NASA Johnson Space Center has been actively working with Rice University to improve dexterous hand design and to develop a method for myoelectric control of multifinger hands. In theory, myoelectric control of robotic hands will require little or no mechanical parts

and will greatly reduce the bulk and weight usually found in dexterous robotic hand control devices. An improvement in myoelectric control of multifinger hands will also benefit prosthetics users.[14]

This list is not exhaustive, but is a representative cross-section of the type of activities conducted by the NASA Telerobotics Program and other government organizations. Additional efforts have extended this coordination to industrial telerobotics research programs, to aid in the transfer of government-developed technology to the U.S. commercial/industrial robotics community. These efforts use two mechanisms to transfer the technology developed by the program.

The first mechanism pairs NASA researchers and commercial developers together to develop space telerobotics technology which is based on commercially-available products. As the terrestrial systems are extended to address the needs of the space telerobotics program by the researchers, the commercial partners are able to identify markets and applications for dual-use implementations of the new technologies, and rapidly incorporate them into new product lines. An example of this is the development of the "phantom robotic control" technology developed by JPL under the Advanced Teleoperation project. This technology has been developed as an extension to the commercial Interactive Graphics Robot Instructional Program (IGRIP) software package from Deneb Robotics. JPL has worked with Deneb to smoothly integrate the extension into the IGRIP package, and negotiated a mechanism to provide this extension to Deneb for commercialization. Deneb has identified a new need for this technology, beyond the original application of space telerobotics, and plans to incorporate the extension into their commercial product line.

The second mechanism pairs NASA researchers with commercial developers to work jointly on the application of space telerobotics technologies to terrestrial problems. The commercial partners bring existing terrestrial robotics systems and capabilities into the project, and work jointly with NASA researchers to improve these systems through the application of space telerobotics technology. An example of this is the Hazardous Materials Handling Robot (HAZBOT) project at JPL, which is being conducted with the partnership of Remotec, Inc, and which is addressing the problem of hazardous chemical spill incident identification and mitigation through the use of robotics. JPL and Remotec worked to apply technologies developed by the Telerobotics Program to improve the off-the-shelf Remotec "Andros" mobile robot to satisfy the unique needs of the HAZBOT project. Several of the specific techniques and mechanisms developed during this process have been delivered back to Remotec for incorporation within their commercial product line.[15]

The program has similar interactions with other members of the U.S. industrial robotics community, such as Robotics Research and Oceaneering. The current program plans include expanding these efforts to include a larger percentage of the U.S. robotics industry.

Technology Requirements for Future Systems

With the advent of these new experimental and operational space robotic systems, the ability for remote manipulation to perform real tasks which offer significant improvements to mission operations, cost effectiveness and mission safety will be proven. But these will still be early generations of advanced space robotic applications. As successive waves of space robotic applications are deployed beyond the year 2000, the goal of intelligent, autonomous space robotics will become more and more important. Technology drivers for these systems include enhanced collision detection and avoidance, advanced local proximity sensing, task level control workstations, improved command and control architectures, fault tolerant architectures, reduced mass and volume, worksite recognition and representation, improved robotic dexterity, advanced supervisory control, and improved overall system robustness.

By combining these next-generation technologies with the operational knowledge gained from applications being flown in the next few years, the first intelligent space robotic systems will be within reach. By then combining the technologies with the development procedures utilized by the current suite of applications, the next generation of space robotic applications will be affordable, even within the ever-tightening budget environment of today's space program.

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MACHINE INTELLIGENCE-
THE KEY TO GUIDANCE AND CONTROL IN ROBOTICS

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SUMMARY

A robotics system is composed of a hardware platform which provides the stability, mobility and manual dexterity; and a software system which acts to interpret the input sensor data and the mission statement and then to create the required excitation to the hardware. Stated in this rather simplistic way, there seems to be little reason for the vast array of laboratories feverously working on the creation of fully autonomous robots. The overall task and its components, however, has proven of intricate complexity, with succeeding layers of hidden problems becoming exposed just as a solution appears eminent.

This paper is concerned only with the software components of a robotics system, and in particular with that portion of the system which comes under the general description of intelligent software. It is a 'stand-off' approach derived from a software engineer's point of view. The intent is to review, from a particular and perhaps novel point of view, the various software paradigms and their intrinsic capabilities and functionalities. This review provides the bases for a detailed map of the current capabilities of software paradigms onto the guidance and control problems of intelligent robotics systems.

The paper is partitioned into two parts: Machine Intelligence as a Robotics Component, and Expectations and Projections. In the first, a perspective of intelligent software is presented which provides the bases for considering guidance and control problems. In the second part, the utility of this perspective is demonstrated by exploring a generic guidance and control architecture. The paper ends by suggesting some approaches for future directions in developments in this field.

PART A - INTELLIGENCE AS A ROBOTICS COMPONENT

1.0 INTRODUCTION

The concept of a fully autonomous intelligent robot has been a reality for science fiction writers for eons. Writers such as Asimov have even postulated rules of behavior for such devices. More recently, Star Trek (an American TV serial) has as a principal character 'Mr. Data,' a highly mobile and highly intelligent Android. Given the spectacular advances in computing through-put available on small low-power silicon chips, and the equally incredible advances in the storage density of memory technology, it seems reasonable to suggest that sufficient computing power and memory can now be loaded onto a mobile robot to fulfill almost any conceivable computing requirement. Indeed, there seems little technological reasons for the delay in creating such a device. Certainly, from a software engineer's point of view, the underlying computational capability is now widely available and a naive assertion is - "It should not take long for the implementation of a really intelligent robot?"

The facts are, of course, that the simplest of human activities are proving of inestimable difficulty in implementation; in most cases because we do not really know how it is that the brain accomplishes its basic functions. It is possible, however, to conjecture at a high level what kind of processing accomplishes our rudimentary and advanced capabilities, and from these conjectures postulate what kind of software paradigms will be needed to emulate these functions. From this approach a general frame work can be established which categorizes the various problems and offers a coherent view of the activities around the world, the key problems that must be surmounted and the potential for near-term advancement.

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Before proceeding, it is important to share a perspective of the complexity of any given problem and to recognize the basic difficulties in its solution. These come in four categories:

i) Unknown, and Perhaps Unknowable: In this category, we place capabilities that are, as yet, not completely understood, such as vision, speech understanding, synergistic insights, etc; all of which, in the end, may not be understandable or completely emulatable. Such problems may require whole new thought paradigms to define the direction of research;

ii) Unknown, and Hopefully Knowable: In this category are capabilities that are not yet completely understood, but which are thought to be achievable with more research. There is a gray area between this category and the first. Speech recognition, for example, may belong to the first, while we hope it belongs to the second;

iii) Known, but Technology Limited: In this category are capabilities that will eventually be solved by the advances of computing technology. Such problems may be solvable given computer power not yet available, but foreseeable; and,

iv) Known and Implementable: In this category are all those things that we are now able to emulate.

It seems important to perceive and appreciate these distinctions. Some of our human characteristics may not be understandable, let alone emulatable. The problem of speech comprehension being a typical example which has been 'near' solution for over a decade. Complete emulation of the human vision system, as a further example, may not be emulatable because we may never understand how we do it ourselves.

Before addressing the intelligence question, it is also acknowledged that some reasonably difficult problems remain in other areas of autonomous systems, such as duplication of the human stability and mobility capabilities. We leave these problems to others, however it may be worth considering where these fit in the problem spectrum.

This paper is presented in two parts, roughly divided into a consideration of intelligence as a robotics component, and a final view of our expectations and projections. First, we propose a general logical model of the robotics problems as seen from a central intelligence perspective. Finally, some general conclusions are drawn. In Part B, the first step is to review the capabilities of various processing paradigms, and then to speculate how these may work in concert to solve robotics problems. The next step will pull all this together and suggest viable paths into the future for the advancement of guidance and control capabilities. The problem of data preparation (sensor fusion and integration) is considered as an example. It is proposed that the goal of this activity should be the appropriate preparation of data for presentation to the various intelligent systems.

It seems important that the model of the problem be appropriate, or at least shared, to provide a common basis for discussion or criticism. We will attempt this first.

2.0 GENERAL LOGICAL MODEL

Each of the disciplines in the field of robotics has a model which characterizes their view of their problem. From the point of view of central intelligence, all other aspects of the robot are simply a means of providing the appropriate data input from a bank of sensors, and the requirement is to create the correct data output to a bank of actuators.

Figure 1 presents a simple and very general view of the various logical levels of interest. Control of the input data stream may be centralized or distributed. In the former, the central intelligence decides the precise command structure to control modifications, extensions or other modifications to the input data stream. In the later, only high level requirements are passed on to the next component.

A version of the physical world is recorded by the sensors, and is acted upon by the actuators. In between, the sensor data is preprocessed (possibly fused and/or integrated) and a state vector presented to the central intelligence. The central intelligence must acknowledge the state vector, interpret it in terms of its world model, derive an appropriate response in terms of its allocated tasks, and create an output vector which is delivered to the actuators.

Figure 2 shows a more complete division of functions of the central intelligence, which corresponds to the hemispheric division of functions in the human brain. In this model, the processing functions are partitioned into three parts. The first part responds to the state vector in terms of automatic and predictable processing algorithms. The second is a more intuitive part, which reacts to the world in terms of a learned response based on successful responses to situations experienced during its lifetime. The third could be termed the reasoning part, which assesses the state vector of the world in terms of logical reasoning based on experience and rules of behaviour.

These three divisions in capability are intuitively appealing. The reactive component can be implemented by algorithms on high speed computing devices, and could be used, for example, to maintain verticality in a robot. The rational part would resolve problems by either inductive or deductive reasoning, based on the known interactions of the attributes of the world model. The intuitive part could respond to situations which are not quantifiable or describable in a manner suitable for implementation in an algorithm, or by a rational logical sequence of deductive or inductive reasoning.

3.0 INTELLIGENT PARADIGMS

3.1 The AI World

Artificial Intelligence (AI) attempts to model decision problems requiring human-like reasoning abilities. The field of AI, as shown in Figure 3, covers many technologies such as machine learning, robotics, natural language processing, vision, speech recognition, and expert systems. Some authors, however, categorize machine learning as separate from artificial intelligence [1]. Each AI technology typically is explained in terms of the reasoning and representation approaches. Representation involves the form in which knowledge is encoded, while reasoning involves utilizing that knowledge to interpret and react to stimulation.

3.2 A World Model and State Vectors

It is very important to recognize that humans and robots perceive the world through a set of sensors, augmented by a model of the world that we, as humans, derive from sociological conditioning and experience. As a species we have been deprived by evolution to a subset of capabilities enjoyed by other species; consider the enhanced capabilities of smell (enjoyed by a dog), hearing (by most other animals), and sight. Our vision system has neither the sensitivity of the cat nor the range of an eagle. Indeed the spectrum of light we detect is limited (no infrared for example). Despite these severe limitations, we have developed a common world-model, and in most cases have derived, through intuition, training and reasoning, processing procedures to respond to our limited sensor inputs. Of course, to a limited extent, we are able to fuse and/or integrate data (vision, hearing, smell and touch) to enhance our survival skills.

The input to any (artificial) processing capability is a data vector representing the perceived state of the world obtained from sensors. This vector can contain strictly numeric entries or descriptive attributes of the world state or possibly both, depending on the requirements of the processing. In terms of the model developed earlier, there are several types of processing approaches to derive the appropriate response. We will consider several in turn.

3.3 Algorithms - A Reactive Response

An algorithm is a detailed description of the data transformations resulting in a predictable and verifiable outcome based on a given input vector. Algorithms are, perhaps, the easiest software paradigm to program, test and - usually - offer the fastest response time on a given computing platform. Algorithms executing numerical data have the additional assistance of high-performance arithmetical units and proven techniques for programming and data manipulation.

Algorithms are normally not included in the class of intelligent software paradigms. Yet algorithms can provide highly intelligent and appropriate responses to input situations. Indeed the processing capability of algorithms can be very complex and include profound assessments of the state of the world and the range of appropriate responses. We will develop the point of view that intelligent software can include any paradigm, providing it has certain attributes to be defined later.

3.4 Fuzzy Logic

Fuzzy logic devices can accomplish some very profound responses to the input state. Fuzzy logic has, at its basics, a means of ascribing membership in a set of classes of various attributes of the world. Thus a particular event can be associated with varying degrees of membership in more than one class (the distribution of membership is fuzzy, rather than binary). Underlying this association is a complete algebra (such as Boolean Algebra) for deriving logical conclusions concerning the impact of a particular set of events.

This approach has been used commercially to adjust the focus in cameras, or to sense and respond to conditions in household appliances.

3.5 Expert Systems (ES)

The term Expert System refers to a generic class of paradigms which, in general, consist of two major components; a knowledge base and an inference engine. The knowledge base contains a representation of the rules, heuristics and experience of appropriate responses in a particular domain. The inference engine is (or can be) a complex procedure for searching through the knowledge base for paths of interconnected rules leading to a conclusion.

The knowledge base can be represented by a collection of rules of the form:

IF (antecedent) THEN consequence(s).

This collection of rules is obtained through a process referred to as knowledge acquisition, which traditionally has meant interviews with human experts who enunciated their procedures in the form of rules for dealing with a particular situation.

The instantiation of the rules in the knowledge base can proceed in a haphazard way, in the sense that rules are entered as they are thought of by the expert, and a particular situation can be tested for completeness and the rule base augmented as gaps are found.

The inferencing engine can be designed to accept an input state vector and to search for a rule with an antecedent which corresponds. The consequence of this rule yields the input to the next search, or the final conclusion. Very complex inferencing procedures have been created in an attempt to emulate the reasoning; both straight-line and circular of the corresponding expert. A typical expert system is divided into four interacting parts. The first part is the knowledge-base containing the problem's facts or other static information and heuristics possibly in the form of rules. The second part is the working memory containing relevant data for the current problem being solved. The third part is the reasoning method or inference engine controlling the organization of the problem data and the route to be followed through the knowledge-base. The fourth part of an expert system is an interface module which interacts with the user or databases. Inferencing can be halted to query the data source (human or otherwise) for clarification or additional data if needed to continue a line of reasoning.

In general, there are two kinds of reasoning methods used in expert systems. The first type works from hypothesized conclusions towards known facts and is called 'backward chaining' [13]. This reasoning is commonly used in diagnostic situations. The second type which starts from a known fact(s) to prove a conclusion is called 'forward chaining.' Forward chaining corresponds to a search from cause to effect, while backward chaining corresponds to a search from effect to cause (for example, diagnosis).

If the rules form a single level hierarchy, the rule base corresponds to a set of cases, as in a case-based reasoning system. Such a situation is a degenerate case and normally the rules are linked in a tree-like structure which must be searched for answers. The knowledge base can be very large, containing in practice several thousands of rules, although such large collections do offer problems in testing and maintenance.

Very complex inferencing algorithms can be devised. Beginning with an initial input state vector, the system can search for a suitable rule which corresponds exactly to the state vector and proceed to explore the consequences. If the state vector is incomplete, either at the start or during the transition of the rule base, it can request more data or suggest possible completion strategies to obtain the mission information.

An expert system becomes a candidate for a solution under the following conditions:

i) Non Algorithmic - solutions are not known in advance;

ii) Domain is bounded and describable;

iii) A recognized and articulate expert(s) is available who can recall all relevant rules; and,

iv) Expert performs task in reasonable time length.

Advantages:

i) Does not rely on large data samples; and,

ii) Explanation of decisions is available.

Disadvantages:

i) Need articulate and available expert;

ii) Typically 12-18 months to develop a useful expert system;

iii) Maintenance of a large system can be difficult;

iv) User must understand shortcomings;

v) Execution time can be slow;

vi) Domain specific; and,

vii) Not efficient for pattern matching.

3.6 Machine Learning

Machine learning, has four main subtechnologies: Induction (learning a general concept from viewing both positive and negative examples); analytic (deductive approaches using past experiences to provide examples and guide the solution for a new problem, i.e., case-based, analogical, explanation based learning); genetic algorithms (produce mutations of examples by selecting the best features of a class and use a selection process to achieve objective); and, connectionism or neural nets. Cased-based reasoning and neural nets are probably the most widely known approaches for machine learning and are discussed below in more detail.

It is important to understand the difference between expert systems and machine learning. For the purpose of this paper, one important difference is the incorporation of new knowledge. In a rule-based expert system, the programmer must analyze all new knowledge introduced by the expert as to its usefulness and role; translate it into a form acceptable to a rule-based approach; program it; and finally, verify and validate the new enhanced program. In a machine learning approach, new knowledge is typically entered as another set of examples (knowledge). The machine analyzes it and performs program modifications. The programmer then verifies and validates the new enhanced program.

3.6.1 Case-Based Reasoning

Case-based reasoning (CBR) has received some attention lately as theoretic concepts are now being applied to real problems [2&3]. This type of reasoning got its start with the theory of Dynamic Memory Structures [4&5].

Case-based reasoning can be defined as the ability to match the facts of a situation against previous ones and adapt the solution to the new case. The central idea behind CBR is that reasoning is done from previous cases and not from "first principles," for example, conclusions are drawn from the available case. This allows a problem solving and reasoning system to avoid known errors and reach a solution in a more guided way, for example, incorporating the solution methodologies found successful in previous cases. The basic method is to first represent cases in terms of features [6], then to resolve the reasoning approaches.

In a CBR system, the input data vector is most often a set of descriptive attributes of the world. The system compares this vector to a stored set of vectors to determine if it can be identified as 'close' to one member of the stored set. In a real sense, the goal is to determine if the systems has 'seen' anything close to the present input vector. If so, then a known response can be executed. This corresponds, in a sense, to storing all the answers; however, there is more to it than this.

In the simplest perspective, a CBR system can be viewed as a sequence of

'IF (antecedent) THEN (consequence)'

statements in which each antecedent represents a case or, it can be viewed as the CASE statement available in most programming languages. This simple construction is augmented by an important extension and by an inferencing capability which can examine the results of the case search and formulate 'intelligent' interpretations of the failure to find exact matches.

A pathological drawback to such a system is the potential for a combinatorial explosion in the number of combinations of the set of input conditions that have to be accounted for. By introducing a tolerance measure on the components of the input vector, a range of input values can be accepted as representing a case. This introduces a certain fuzziness into the acceptance criteria. An important advantage follows, however, since depending on the definition of the attribute tolerances, only a representative set of state vectors need be stored. This representative set can be chosen to reduce the number of cases that must be stored.

CBR systems, can also have a reasoning capability beyond simple comparisons. Under conditions in which an acceptable match is not found, the system can determine the closest matches, and/or determine which attributes are causing the mismatch. This information can be used (by another intelligence source; say an expert system) to postulate new cases or to modify the definition of the attributes to extend the virtual volume covered by a particular case.

CBR systems, therefore, can:

i) Identify classes of inputs related by some definition of a closeness criterion;

ii) Provide reasoning capability about novel inputs; and,

iii) Dynamically define new cases. New cases can be added when sufficient evidence exists that might represent an interesting (i.e., potentially re-occurring) phenomenon.

These systems can handle qualitative or quantitative data or mixtures of the two. Such systems while useful in their own right, often can be used to provide preprocessing of input data. They answer the question - "Have I seen this situation before?" In addition to a definite answer, they can provide closeness measures which can be used to determine how close the new situation is to 'reasonably close' stored cases. The results of this pre-processing can be used to respond directly to the input excitation, or provide input to further processing. The pre-processing will, hopefully, reduce the search time of further processing elements for an appropriate response.

A CBR system becomes a candidate for a solution to a problem under the following conditions:

i) Each case can be represented in terms of features;

ii) A criterion is available for comparing new cases to existing ones; and,

iii) Rules can be used to modify the attributes of solution.

Advantages:

i) When decision approach is unknown; and,

ii) Incorporates failure and success features in order to make predictions concerning viability.

Disadvantages:

i) Need a large and complete set of case records; and,

ii) Need a large vocabulary set.

3.6.2 Artificial Neural Networks (ANN)

The study of ANNs predates all other forms of artificial intelligence activity. An artificial neuron emulates the processing of the human neuron by computing the inner product of a set of stored weights and an input vector. The inner product is usually subjected to a non-linear smoothing function (e.g., a sigmoid). Arrays of these neurons are assembled to relate an input vector to a set of outputs. The substantial difference between an ANN and other forms of intelligent systems are routines that have been derived that permit the weights of each neuron in an array to be 'learned' by repetitive presentation of the whole set of inputs. Weights are adjusted incrementally based on the error generated by the network and the predetermined correct response. While the theoretical basis for the training routines is well developed, in practice some uncertainty exists in achieving convergence due to the very complex topology of the error surface.

A vast array of neural topologies now exist, and research on these and real-time responsive arrays is currently in progress. Classical ANNs fall roughly into three classes: those that map an input vector onto an appropriate response vector; those that minimize an energy function; those that can learn in real-time (dynamically). Real time networks (called ART Nets) are able to dynamically learn new patterns based on the repetition in an input sequence, and forget patterns which no longer occur with a sufficient repetition rate.

The major strength of ANNs is the ability to learn the mapping between the input vectors and the desired output vectors. This ability to learn means that the relationship need not be expressible by any algorithm or set of rules. The draw-back is that examples of the input vectors (and the correct response) must be plentiful to permit convergence of the training procedure. In this sense, an ANN emulates the more intuitive aspect of human intelligence, in that conditioned or learned responses can be built into the neural network by repetitious training (much as with a human) without explanations.

With the exception of the ART networks, neural network responses are fixed at the conclusion of training. New inputs can only be accommodated by starting the training process from the beginning.

In some situations, the output vector of a neural network can be considered as defining the case represented by the input vector. Identification of a case drives a response reaction. If a clear decision is not possible, the output can often be interpreted as giving a closeness measure to the existing cases. This is similar to a fuzzy membership function and this information can be passed on to another paradigm (such as an ES) for interpretation.

An ANN can be considered as a potential solution for achieving machine intelligence under the following conditions:

i) Input vectors can be related to a known output (e.g., pattern matches); and,

ii) A large numerical data set is available representing input conditions and the appropriate classification. This is often referred to as the training set.

Advantages:

i) Designated Input-output patterns can be learned; and,

ii) Multiple patterns matches can arbitrarily partition a complex space.

Disadvantages:

i) Cannot provide rationale;

ii) Data sets must be representative; and,

iii) Development time is difficult to predict.

3.7 An Overview - ANN, CBR, ES

A CBR system and an ES have many similarities. They are distinguished from a ANN by one major feature: An ANN is a closed system, in that the internal processing is largely indecipherable, while the inferencing process of a CBR or an ES can be supplemented by external interactions with the environment. The similarities on the other hand are striking. All three attempt to interpret an input state vector and derive some conclusion or action plan. Thus functionally they are the same. The differences lie in how the internal processing is originally derived and in the mechanisms for arriving at a conclusion.

A CBR could be thought of as a large CASE statement on the input vector. If a case is found, then an action results. The immediate extension to this common programming idea is that the components of the state vector can carry a tolerance, so that items in the state vector which are close (in some sense) to the stored case, can be accepted as equivalent to the case. In addition, as mentioned previously, if no stored case is found, the system can list the closest cases and or query the data source for variations of the data, if appropriate.

In addition, a CBR can dynamically add new cases according to some criteria; a feature which is not possible with an ES without human intervention. The basic weakness of a CBR system is the single level of the hierarchy connecting input with output. This clearly limits the reasoning ability of a case system. A CBR system serves a very useful function as a pre-processor which quickly addresses the question - "Have I seen this situation before? and what did I do about it?"

An ES possesses the ability to execute complicated hierarchical strings of reasoning linking cause and effect (or vice versa). In addition, the inference engine can create a dialogue with the data source, during the reasoning process to request more or variations of the data input which may support a particular path of thought. The weakness of such a system is that the rule base represents the world view of the system and, therefore, must be complete and reflect all possible outcomes of results of the state vector, which suggests that the outcome must have been foreseen and the appropriate rules embedded in the system.

3.8 Vision Systems

Vision systems are often considered as a separate activity in the pursuit of artificial intelligence. Robotics vision systems generally includes any sensor information designed to develop and maintain a (geometric) knowledge base for path planning, collision avoidance and task planning. Sensor information can vary, depending on the task and the environment, from a dense pixel representation of the environment obtained by standard television or infrared, to radar, laser, and/or sonar range information, or Doppler scanners.

The task is to interpret the available information and respond with a guidance plan which accounts for the perceived terrain and the original goal of the mission.

One approach to obtaining a view of the world is multiresolution image processing as proposed by JPL [7]. This system illustrates a solution to minimizing the processing.

The system begins with an image of 512 x 512 pixels, then successively selecting every other pixel to create subsampled images at 256 x 256, etc., down to 16 x 16 pixels. The goal is to process images at the lowest possible resolution for the given task. The results of this lower level processing is used to guide a "window of attention" to those parts of the higher resolution images that need to be analyzed in detail. Special purpose processors could be assigned to each window to achieve real-time response.

The software tools developed at JPL include those:

i) For manipulating image pyramids;

ii) For spawning windows-of-attention based on a variety of cues;

iii) For creating new pre-attentive cues for spawning windows-of-attention;

iv) For analyzing the windows for motions, texture, and other properties;

v) Deciding when and how to move the window-of-attention to a lower (or higher) array; and,

vi) For matching window with other templates.

The details of the software paradigms are not given in the paper, however, for our purposes it is clear that several things have been accomplished:

i) A sensor system has been adopted to produce a pixel stream representing the world;

ii) The pixel stream has been processed (algorithmically) to create a pyramid of images of lowering resolution; and,

iii) A host of software routines have been set up to derive appropriate information from scanning the images and moving across the images as seen to be necessary.

The JPL system was designed to interact with an operator (telerobotics) for guidance in feature and object tracking, as well as, for scene segmentation and object modeling. It seems a small step to create surrogates of the operator's experience and knowledge and create a fully autonomous system.

4.0 HYBRID SYSTEMS

4.1 Introduction

A hybrid artificial intelligence architecture can be constructed by combining one or more artificial intelligence technologies such as expert systems and machine learning. Many systems typically require more than one AI technology to successfully represent the knowledge and implement the required reasoning abilities.

It is clear that the emulation (in software) of human intelligence will require the creation of various kinds of responses to the environment. Our proposal is that combinations of the various paradigms operating cooperatively in a hybrid system will be the final answer to achieving intelligence in machines.

In this section we propose a model of an intelligent machine with a partition of capabilities deemed necessary to achieve human-like responses to new situations. The model accounts for rational, intuitive and reactive responses.

4.2 A Brain Model of a Hybrid System

A human is alleged to have a brain with the rational function largely performed on one side and the more intuitive functions on the other. In addition we have many reactionary type functions performed by the spine and by lower level reptilian portions of our total brain. If this partition of the brain has been favoured by evolution, there is perhaps some benefit to exploring the need for such partitions in creating an emulation of human intelligence.

In terms of the attributes ascribed to the various paradigms in the preceding, it is clear that, in a broader sense, the various AI paradigms can be grouped into similar brain-like functional divisions.

Algorithms clearly correspond to the reactive portion of our brain functions. CBR and ES correspond to our capability for logical inferencing based on knowledge, acquired from experience and/or other instruction, which may not always be intuitively obvious. ANNs correspond to our intuitive capability for 'sensing' that some conclusion follows from an observation that may not be derivable as a logical inference.

It seems reasonable to suggest that guidance and control systems with a wide range of capabilities must emulate these three capabilities if they are to respond to a variety of conditions through out their task assignment.

If such is the case, then clearly there is a need for a methodology for specifying, designing, implementing, testing and maintaining such a system. We have proposed such a methodology [8], however it is beyond the scope of this presentation. It is worthwhile to support this conclusion by examining some current work in developing hybrid AI systems.

5.0 HYBRID INTELLIGENT SYSTEMS

5.1 Introduction

In this section, we will consider the integration of ES and ANNs to create complementary hybrid architectures. These two paradigms are sufficiently mature to be serious contenders for some decision processes in a G&C system. Integrating CBR and ANNs impose the same set of problems.

The direct integration of neural networks and expert systems is not straight-forward for a variety of reasons:

i) The nature of the data in a neural network is numeric, while in an expert system it is symbolic;

ii) Relations in neural networks are causal and represent associations, while in expert systems relations are structured and allow combinations; and,

iii) The characteristic behavior in a neural network is self-organization, while in expert systems the combinatorial capability of structures is the major feature.

These distinctions characterize and emphasize the differences in the two approaches, however, they also provide clues as to how they can be complementary. Integrating the capabilities of the two paradigms involve the preliminary partition of the original problem, the sharing of data, and the global control of interaction.

There are two basic integration approaches:

i) <u>Autonomous Functional Units</u>: The most general architecture would be composed of an interconnection of functional units each chosen to optimize the performance based on the type of decision process to be executed; and,

ii) <u>Embedded Sub-Systems</u>: The simplest architecture from a control point of view is to embed one system within the other. In this way the embedded system is called when needed to supplement the capabilities of the other. Typical structures, for example, could include an expert system which interprets the results of a neural network, or a neural network called to analyze or preprocess a data set for an expert system.

The Autonomous Functional Units architecture offers the greatest potential for implementing a wide variety of problems, however, it also offers the greatest challenge in design, implementation and testing. Such an organization requires an explicit or implicit control mechanism which directs the propagation of decisions through the various functional units. This control can be established by a separate task-allocation or by the fixed interconnection of the units.

There are two important considerations which distinguish integrated systems from others: Representation and Global Inferencing.

5.2 The Representation Issue

Three approaches have been used for representing an integrated expert system/neural network:

i) Data Interface: The easiest is to represent the individual functions independently and to communicate by means of a data interface. This reduces the integration of the data requirements for each;

ii) Node Links: This involves linking a component of the expert system knowledge base (e.g., a fact, a frame, or an object) with a node in the neural network. This allows both systems to access information simultaneously; and,

iii) Connectionist: The expert system becomes a node in the neural network. An update mechanism is responsible for maintaining a consistent knowledge representation, and for ensuring other components are aware of the change.

Updating mechanisms have two forms:

i) Synchronous: Regularly updates, based on a clock signal; and,

ii) Asynchronous (as-needed): The knowledge representation of an object or component is updated only when that component is queried. This is obviously less resource-utilization intensive than a synchronous update.

Consistency management determines the current correct value of a symbol/node. Consistency management acts as a mediator between the two systems. This is obviously important if the possibility exists for disagreement at any point in the over-all inferencing process. There are three common approaches:

i) Recency: The manager takes the value that is most current, regardless of which system it is from;

ii) Confidence: The manager compares the level of activation on the neural network node to the level of certainty generated by the expert system, and selects the highest value; and,

iii) A-priori: The consistency is based on always accepting either the expert system or the neural network.

5.3 The Inferencing Issue

Global inferencing in an integrated system is either centrally controlled or is distributed:

i) Central Control: This implies a single module responsible for guiding the inferencing process. An expert system can be designed to switch between modules depending on their responses or other performance criteria, or a neural network can be used to focus the search and choose the next module; and,

ii) Distributed: This implies that control is based on some form of interaction either based on the interconnections or on some interaction guidelines.

Several different systems for the classification of hybrid architectures of neural networks and expert system have been proposed. Among them, the system proposed by Caudill [9] and the system proposed by Medsker & Bailey [10], are typical and represent different views of the classification of the ES-NN hybrid architectures.

Caudill's system (the CD system) includes five classes of the ES-NN hybrid architectures: formal separation; buried networks; explanation by confabulation; digging for secrets and two-step tango. In the CD system, the classification is primarily concerned with the class differences in the functionalities of expert systems and neural networks.

Medsker and Bailey's system (the MB system) also includes five classes of the ES-NN hybrid architectures: stand-alone; transformational; loosely-coupled; tightly-coupled; and, fully-integrated. In the MB system, the class boundaries are not well defined. In some classes, the classification of the ES-NN hybrid architectures is appropriate based on the characteristics of their software architecture, however, is inappropriate in their functionality characteristics.

In a complete classification system, the functionalities of expert systems and neural networks in the hybrid architectures and the characteristics of software architecture should all be considered. To make up the deficiencies of the CD system and the MB system, we proposed a new classification system of the ES-NN hybrid architectures (the CES system). The CES system includes seven classes: autonomous functional units; closed embedded sub-systems; open embedded sub-systems; simulating externally; simulating internally; transformational systems; and, developmental tools. In defining these classes, we considered the difference in the functionality of expert systems and neural networks in the ES-NN hybrid architectures as well as the characteristics of software architecture.

The seven classes will be defined in the next seven sections. For each class, its application, advantages and disadvantages or limitations will be discussed.

5.3.1 Autonomous Functional Units

This class is the mainstream in the study of the hybrid architectures of expert systems and neural networks. In this class, each expert system or neural network is an autonomous functional unit. In a decision procedure, each decision node is implemented by an expert system or a neural network independently. This class is applicable for the cases where a large and complex problem can be broken into small sub-problems; each sub-problem would be solved by individual expert systems or neural networks.

A classic delivery system problem provides a good example to demonstrate how the problem can be solved using the autonomous functional units technique. The problem is to create a system that can schedule truck deliveries for customers. This problem includes two distinct sub-problems: which packages should go on which track; and, what route each truck should take for the most efficient delivery path.

The first sub-problem is primarily concerned with how to reasonably assign a package to a truck, based on the destination, weight and size of the package, the characteristics of other packages, and the characteristics of various trucks. The expert system is chosen since the package-assignment rules are not difficult to articulate.

The second sub-problem is optimization, in which the best path for a given set of stops must be determined. This kind of challenge is not easily solved by a set of rules as there exists the vast number of possible destination combinations. On the other hand, certain neural networks deal easily with such optimizations. They can generally provide a nearly optimal path and do so quickly.

This example shows an excellent decomposition of the overall problem and an optimal functional allocation between an expert system and a neural network. Using each kind of system to tackle the parts of the problem to which it is most suited, provides both relatively easy implementation and reliable operation.

In implementing the hybrid architectures of this class, the data coupling between an expert system and a neural network is important, since it affects the efficiency and performance of the final system. There are basically two coupling approaches: loose coupling; and, tight coupling.

5.3.1.1 Loose Coupling

The loose coupling approach is characterized by a data sharing mechanism involving external data structures. The storage of intermediate data and its formatting for use by the next process is done in the data structure.

This coupling approach offers several benefits to the integration of expert systems and neural networks:

- i) They are relatively easy to design and develop;
- ii) They are amenable to the use of commercial development platforms; and,
- iii) They are easy to maintain.

There are, however, three major limitations to this approach:

- i) There is often a great deal of redundancy in the development process;
- ii) The operating time is usually longer, because of the required interfaces between the sub-systems; and,
- iv) There is a high communications overhead.

5.3.1.2 Tight Coupling

Expert system and neural network share common memory resident data (instead of passing data structures or using external data files). This improves the interactive capabilities (compared to the loose coupling approach) and enhances performance. Tightly coupled systems often appear to have the same architecture as a loosely coupled system, however, if properly designed, they are faster because data is shared directly (without intermediate external data structures or transformations).

The tight coupling approach offers several benefits to the integration of expert systems and neural networks:

i) They have reduced communications overhead, and improved run-time performance (compared to loosely coupled systems);

ii) Several commercial development platforms are available (e.g., Gensym's Neuronline); and,

iii) They offer design flexibility and robust integration.

There are three principle limitations:

i) The development and maintenance complexity increases due to the internal data interface;

ii) The system suffers from redundant data gathering and processing due to the independence of the two systems (similar to loose coupling); and,

iii) The verification and validation process is more difficult (particularly for embedded systems).

5.3.2 Closed Embedded Sub-Systems

In this class, one system is embedded within the other to implement some of the functions. Of the latter, however, the embedded system is transparent to the user. In a sense, this class contains the embedded sub-systems architectures which are strictly defined, compared with the embedded sub-systems architectures described in later which are loosely defined.

There are two known, typical approaches in this class: a neural network as the rule firing mechanism in an expert system; and, neural networks as the knowledge base in expert systems.

5.3.2.1 Neural Networks as the Rule Firing Mechanism in Expert Systems

Consider the role of the inference engine in the rule-based system. During execution it must perform at least three tasks: match the state of the world to the IF-clauses of the production rules in the rule base; select one or more of these rules; and, fire the rule while computing the consequences of the firing. This match-select-fire operation is a minimal description of a garden-variety expert system. But the first step in the process is to match the state of the world to the conditional clauses of the rules, more specifically to pattern-match; and pattern-matching is exactly what neural networks do best.

The basic idea is to bury a neural network inside the inference engine of a rule-based system and use the neural network to perform highly efficient and intelligent selection of the next rule to fire. The obvious benefit would be that the resulting expert system would run faster and select more intelligently the correct rule to fire in cases of multiple matches.

The approach would benefit very large rule bases in which sequential rule-matching can take a long time, and in systems that frequently have several rules that match the current state. The rule-based system would leverage-off the parallel nature of the neural network to improve its efficiency and performance.

5.3.2.2 Neural Networks as the Knowledge Base in Expert Systems

One of strengths of neural networks is their associative memory capability, which can be utilized to build the knowledge base in an expert system. The neural network memorizes the facts during its training. Within the expert system, the neural network's input and output nodes are used as the outlets of the facts. Each instance of the pair of input and output patterns provides a fact to the expert system.

The embedded neural knowledge base efficiently and compactly stores a large volume of facts. However, the issue of knowledge base updating in such an integration architecture can be difficult, depending on what type of neural network is used. If the incremental retraining (accepting new facts, with no need of retraining all previously accepted facts) is possible, the incremental updating ability of the neural knowledge base clearly is an advantage of the integration architecture. If the incremental retraining is not allowed (e.g., in the backpropagation neural net), this becomes an obvious drawback.

Applications of this technique include diagnosis, pattern recognition and classification.

5.3.3 Open Embedded Sub-Systems

In this class, one system is used as the main system, the other is used as the secondary system to be called when needed to improve the performance of and/or to supplement the capabilities of the main system. Both the main system and the secondary system are invisible to the user. This class differs from the autonomous functional units class in that the hybrid architecture of this class only implements one node in a decision procedure. It is considered that this class contains the loosely-defined embedded sub-systems architectures, compared with the strictly-defined embedded sub-systems architectures.

Typical hybrid architectures in this class include an expert system used to augment the explanation facility of a neural net.

5.3.4 Expert Systems Interprets The Results of Neural Networks

In the complete system, an input is presented to the network and the network provides the correct response during normal operation. When the user asks for an explanation, the expert system considers the original input pattern as well as the neural network's answer. It then backward chains from the answer to the input pattern, constructing a plausible chain of reasoning to explain why this answer may be correct. In essence, it rationalizes an explanation on the spot, making it correspond with the neural network's response.

This sort of rationalization response provides the user with reassurance that the neural network is operating properly without relying on the rule-based system to generate the solution. The rule-based system does not have to be detailed or complete; it only has to be complete enough to justify the answer to the user. This sort of post-response rationalization is probably a lot closer to the way people solve problems than we would like to admit.

5.3.5 Simulating Externally

In this class, a hybrid architecture appears to be a network. Internally, each node of the network is a symbolic information processing mechanism, which can be as simple as a concept node in the knowledge structure built in an expert system, or as complex as a complete expert system. Externally, the network is a mimic of a neural network, two nodes communicates through the propagation of numeric information along the interconnection between them. Connectionist expert system systems [11] and macro-connectionist distributed knowledge-based system [12] are two good examples of such a hybrid architecture.

5.3.6 Connectionist Expert Systems

Connectionist expert systems, in general, rely on local knowledge representations, as opposed to the distributed representation of most neural networks, and they reason through spreading activation. Connectionist expert systems represent relationships between pieces of knowledge with weighted links between symbolic nodes. Such systems have been used in medical diagnosis, information retrieval and analysis, and pattern classification.

The potential benefits of such a system include:

i) Robustness, improved performance, and increased problem solving capabilities. The robustness and performance improvements derive from the dual nature of the knowledge representations and data structures; and,

ii) A properly designed integrated architecture can yield a broad range of functionality - such as adaptation, generalization, noise tolerance, justification, and logical deduction.

There are several limitations:

i) There is some complexity involved in specifying, designing and building fully-integrated models;

ii) There are no development tools; and,

iii) Verification, validation and maintaining such systems is difficult.

5.3.7 Simulating Internally

In contrast with the simulating externally class in which the neural network's external attributes, the representation and global inferencing mechanisms are simulated, the simulating internally class is concerned with the neural network's internal representation.

Basically, the way to find out the internal representation of a neural net is to first train the neural network to solve the problem and then reverse-engineer it to determine the features the neural network is using to make decisions. For example, in the training of a neural network for an alphabet-recognition task, we could force some of the neurons in the middle layer to look for obvious features like vertical straight lines or curves of various sizes and locations. These neurons then become the designated feature detectors. By analyzing the behavior of these feature detectors, it may be possible to determine how the neural network makes decisions.

There are basically two benefits from doing so:

i) Access to more detailed information on how the neural network makes decisions, which is obviously useful when the neural network must be able to explain what it does; and,

ii) Study the nature of distributed representations and how the brain might process and store information.

There are several limitations:

i) There is no guidelines on how to train a neural network to set up feature detectors in the middle layer. Even if these guidelines existed, the control of this type of training may be tedious; and,

ii) The post-analysis of the behavior of the feature detectors may be difficult.

The applications of this hybrid architecture class include image processing, feature extraction and decision making.

5.3.8 Transformational Systems

The expert system is transformed into a neural network or vice versa. A typical situation might be that the development system was chosen as a neural network because the application was data-intensive and there was a need to generalize and filter errors in the data. The delivery of an expert system was chosen because of the need to document and verify the knowledge used to make the decisions, and justification of the decision was needed. On the other hand, an expert system could be converted to a neural network because it was incapable of solving the whole problem, or the speed, adaptability, and robustness of the neural network is required. Knowledge from the expert system is used to set the initial conditions and to derive the training set for the neural network.

Transforming one system into another can offer several benefits:

i) They are often quick to develop and require maintenance of only one system;

ii) Development occurs in the most appropriate environment; and,

iii) The delivery system is the most appropriate to the operational needs.

Limitations of this approach are two-fold:

i) There is no automated means of effecting the transformation; and,

ii) There is no known method for accurately and completely performing the transformation.

Despite these limitations, this approach has been used many times, which suggests that with reasonable systems such transformations are possible. The question becomes "Which system should be used for development and which for operation?"

5.3.9 Developmental Tools

In this class, one system is used to assist the development of the other. There are basically two approaches: neural networks extract expert system rules; and, expert systems control neural network training.

5.3.10 Neural Networks to Extract Expert System Rules

First, a neural network is trained to solve the problem at hand. Then, the trained neural network is used to generate a set of rules based on the given input data. Finally, the generated rule-set is used to construct the rule-base of an expert system.

In effect, the neural network is trained to be the expert in the expert systems development. The obvious use of this procedure is for problems where no expert exists to construct a rule-based system, but where the properties of a rule-based solution are desired. Alternatively, this approach can be used to supplement a human expert who is having trouble articulating the domain rules.

This process has the obvious drawback of requiring the developers to go through the development procedure for both the neural network and expert system. Nevertheless, in some cases, this technique can be very useful for helping an expert articulating rules, providing an expert with a set of sample rules that can be edited as appropriate and substituting for an unavailable expert.

6.0 SUMMARY

It has been proposed that fully autonomous robotics systems possessing intelligent guidance and control capabilities will necessarily utilize 'intelligent' software paradigms. Further, it is suggested that these paradigms will be used in hybrid combinations to simulate the various capabilities of the human brain.

A hybrid brain model was proposed with several of the well known paradigms allocated to one of three partitions. This or some model like it must eventually provide the intelligence capabilities of an intelligent robot. What is needed is a complete methodology for deriving the appropriate allocation of functions to the available paradigms, and a means of communication between each. Evidence is already appearing in the literature of the use of such systems and it is anticipated that they will become increasingly common over the next few years. What has failed to appear yet is a suitable computer-aided system engineering (CASE) platform for developing each paradigm and for linking and testing the result.

Let us conclude this portion of the presentation with some philosophical comments on machine intelligence derived from 'intelligent' software. An intelligent machine is capable of more than an appropriate response to a predefined situation; intelligence in machines (and humans) is usually thought of as the ability deal with variations on a set of situations, and the ability to reason about the most appropriate response to new situations. In the limit, perhaps, intelligence is the ability to carry out a mission given unforeseen circumstance, and to survive under these circumstances, even if the mission is aborted. The human race may already be undergoing such a test of intelligence.

MACHINE INTELLIGENCE- THE KEY TO GUIDANCE AND CONTROL IN ROBOTICS

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PART B - EXPECTATIONS AND PROJECTIONS

1.0 INTRODUCTION

In this part we wish to accomplish four goals: to review some examples of hybrid systems; to illustrate a generic G&C architectural model; to point out how current and future research will impact the capabilities of G&C software and finally to suggest an important distinction between military and civilian requirements in this area. The later item will be of particular importance to those formulating research projects and to those in a position to fund them.

2.0 PROGRESS IN HYBRID SYSTEMS

The literature contains many examples of hybrid distributed architectures which fall roughly in the proposed classes. In the following sections several will be chosen to illustrate some of the categories.

2.1 A Resource Projection System

Hanson and Brekke [14] developed a system for projecting manpower and resource requirements for maintaining networks of workstations at NASA. The overall function of the system was to estimate the resource requirements and the completion time for the services requested by customers. A service request input is presented as a list of activities required. The output of the system is in the form of spreadsheet files, in which for each activity required, the manpower and resource allocated and the date the jobs to be completed are presented.

The major part of the required output is the allocation of resources, which can be obtained using an expert system. An expert system can properly allocate the manpower and resource for the service requested, based on the knowledge (rules) acquired from managers and technicians. However, another part of the output is an estimation of the completion time for the activities required, which will be more easily obtained by using a neural network. A neural network can be trained using historical data, in which the time needed for different types of activities in the past services are present. Thus, the complete system output can be obtained using an expert system plus a called-up neural network.

In the operation of the system, a service request, in the form of a list of activities from a Service Request Data Base (SRDB), is first preprocessed to produce data files suitable for the neural network and the expert system. The expert system allocates the resources according to the service requested and, in the meantime, it also calls up the neural network to obtain the estimate of the completion time for the given activity list. Finally, the expert system produces the output in which the resource allocation results and the estimates of job completion time are combined.

This system belongs to the *closed embedded subsystems* class in the CES classification system for ES-NN hybrid architecture. The use of the neural network in this system is to provide the expert system with a knowledge base which stores the facts "(activity, completion time)."

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2.2 A Process Control System

A process control system called "SCRuFFy" [14] was designed for the control of mechanical systems in which sensor feedback is needed to monitor the status of ongoing processes. The overall function of the system was to track changes in the sensor signal to detect error conditions in system's operation so corrective actions can be taken before serious errors are committed.

In general, a procedure of process control, based on the sensory feedback, includes these tasks:

i) Converting the sensor signals from analog to digital;

ii) Identifying and classifying the error conditions contained in the received sensor signals;

iii) Tracking the error condition changes, which is needed since an action to be taken against an error condition can be determined only after the continuous change of such error condition has been observed over time; a drastic correction action based on a single input of error condition change is not expected, as it would probably damage the machinery; and,

iv) Making a decision to determine which action should be taken to correct the error condition.

The SCRuFFy system uses a neural net to accomplish the error condition classification task. In general, to determine the situations in which a statistically-based classification method (such as the backpropagation learning) can be used the criteria are: the cost of observation should be low; the features of the class may or may not all be presented; the set of classes is known prior to classification time; the classifications are based on statistical criteria; and, the hierarchical structure of the classes is either not necessary or used in only a limited manner. The classification of the system's operation (error or normal) conditions based on the sensor signals is a case fitting these criteria: sensor data is obtained cheaply at a high rate of speed; features of the class may be undetermined (necessitating a learning algorithm); classification of the signals is desired to match known categories; classification is based on high-order statistical correlations between features in the signal; and, no hierarchical categorization of the signals is typically performed. Thus, the neural net is chosen here to accomplish the task.

The SCRuFFy system uses an expert system to accomplish the decision making task. Making intelligent decisions based on the received sensor signals is very different from classifying these signals. Such decisions may require merging a long time history of sensor results; all features of a situation may need to be present before expensive corrective operations would be authorized; the set of all possible problems may not be known, the recognition of a problem is often context dependent; and, hierarchical structure is often used in the decision making processes. Thus, the neural networks approach seems unsuited, and such a task remains the domain of traditional AI, such as the expert systems approach.

The SCRuFFy system uses a symbolic analyzer to accomplish the error condition change tracking task. This symbolic analyzer also is used to transform the numerical output of the neural network to the symbolic data required by the expert system, which is probably more important from an ES-NN integration point of view. The symbolic analyzer produces the symbolic information describing the error condition changes over time and puts it into a blackboard (or working memory). Thus, a blackboard-based expert system can make control decisions based on this information.

During operation, the signal processor converts the form of sensor signals from analog to digital (numerical) for use by the neural network. The neural network, which was trained to identify error conditions in sensor signals, indicates whether the operation mode of the system is normal or erroneous based on the output from the signal processor. The output from the neural network is fed into the symbolic analyzer. The symbolic analyzer tracks the changes in the error condition and converts this information into symbolic form for use by the expert system which prescribes corrective actions against the error conditions. The symbolic error condition change information is stored in the blackboard, which the expert system uses to make the decisions on corrective actions.

The SCRuFFy system belongs to the *autonomous functional units* class in the CES classification system for ES-NN hybrid architecture. The expert system and the neural network in the system are *loosely coupled*, as they do not share common memory resident data and the symbolic analyzer does a data transformation between them.

2.3 A Hypothesis Testing System

A general problem solving system was developed by Gutknecht, Pfeifer, and Stolze [15], which combines the three paradigms to reason about and solve problems, including neural networks, expert systems and case-based reasoning. The overall function of the system was to learn how to focus on a problem and narrow down to likely hypotheses and questions to find the solution of the problem.

This system was expected to solve a problem in a way that is similar to the way human experts operate. A human expert first has a "case base" in his mind, which contains his knowledge of what hypotheses should be raised and what tests should be done for evaluating the hypotheses. When a problem occurs, the human expert, based on knowledge stored in the "case base," finds and rates different hypotheses and possible tests according to the given conditions. Through a certain number of hypothesis-and-test iterations, the human expert then focuses on the best course of action. After the problem is solved, his "case base" is updated with his performance and experience gained in solving this new case.

In the similar way as a human expert solves problems as described above, the system includes a case-base to store information from observations of human experts' choices of hypotheses and tests. This case-base is updated when the system is used and new instances of expert performance are observed. The system includes a neural network trained to recognize possible hypotheses and tests according to certain conditions of a given problem. This neural net accesses the case-base during initial training and for retraining as needed. The system also includes an expert system which judges the hypothesis test results and determines the course of action required for solving the problem. The expert system accesses the case-base for learning new rules and/or modifying old ones.

The system belongs to the *autonomous functional units* class in the CES classification system for ES-NN hybrid architecture. The system provides the architecture such that the user calls to the neural network and the expert system as needed. The neural network and the expert system are *tightly coupled* in the system, as they share the case base.

3.0 A GENERIC G&C ARCHITECTURE

Any system of guidance and control is finally limited by the information supplied by the sensors. It is always an assumption that the more complete the information about the state of the world the more intelligent can be the responses. Of course the effectiveness of the responses is limited by the capabilities of the actuators. It is reasonable to conclude that a complete system is first decomposable into sensors, actuators and an interpretation and response component.

For vehicles, at least, the available control mechanisms can be as extensive as those supplied to a human operator with modifications to accommodate the drive mechanisms. It is therefore the sensors and subsequent processing that usually receives the most attention.

Determining the state of the world is usually done by an array of sensors measuring different features, which are then combined to produce a description of the world. The question of sensor fusion and/or integration has been a challenge for many years. The major challenge being to structure the data available from the sensors to a data stream suitable for interpretation and control decisions.

Data fusion and integration should be designed to present the appropriate data fields to the interpretation and planning functions of the robot.

The sensor readings themselves may be subject to error and uncertainties caused by their intrinsic ability to represent the world, and by inherent uncertainties due to noise. Most importantly, the significance of the readings may be unknowingly jeopardized by the active influences of an enemies attempts to alter the appearance of the world. Such attempts have a long history dating back to radar and radio jamming in World War 2. It is still possible to jam a sensor array and nullify its utility. While effective, such techniques are primitive compared to techniques employing deception. Deception is an attempt to create a reasonable but incorrect version of the world state by influencing the sensors. Many technological advances are making this both more likely and more difficult to succeed. The impact however motivates the requirement for multisensor arrays and very intelligent processing.

There are four aspects to data fusion and integration:

- i) Redundancy;
- ii) Complementarity;
- iii) Timeliness; and,
- iv) Cost.

Fusion of data refers to a combination of different sensor information into one representational format. Integration refers to the (synergistic) use of information from different sensors to accomplish a task of the system. Fusion is generally an algorithmic task while integration implies a certain amount of intelligence in the procession modules.

Waltz and Buede [16] have proposed a generic command and control architecture that includes multisensor integration and fusion functions and a distributed intelligent architecture. We will look at the intelligence aspects of this early proposal and suggest what additional features could be added to create an intelligent completely autonomous system.

The proposed functions of the four steps shown in Figure 6 are:

i) The sensor bank collects data from the environment and transmits the data to the multi-sensor integration and fusion subsystem;

ii) The multi-sensor integration and fusion subsection fuses and integrates the data to find any events or targets of interest. The fused information representing the possible targets or events which influence the current situation are then sent to the decision support subsection;

iii) The decision support subsection creates, analyses and ranks alternative courses of action; and,

iv) A human selects a course of action (which could influence the current situation).

The system contains multiple feed back loops for distributed control. Operation is initiated with a query from the human for recommended courses of action. Based on some parameters supplied by the human and the assessment of the current situation the system recommends a course of action. It can query the multi-sensor fusion and integration unit if necessary.

In order to suggest the requirement for intelligent software it is worth briefly looking at the functions performed by the major modules. The process of data fusion starts with each sensor sending detection report or tracks to the queue from which they are transformed to a common space-time coordinate system (this is necessary because of different data rates and time responses).

The process of combining the collected data to enable the attributes of a target (e.g., its identity, intent, future behaviour, etc.) to be inferred is the core function of the multi-sensor integration and fusion subsystem. In the decision support system, the first module is an expert system. The arrival of new sensor data causes a forward-chaining process to search for the rule with the appropriate antecedent, and the situation data base being updated with the consequence.

By backward chaining, a hypothesis can be searched for matching antecedents, and the sensor management function can be directed to search for data which might support the required antecedent.

There are of course many other approaches to processing sensor data; they share the common objective of providing a reliable data reactor for interpretation and decision making.

4.0 G&C SYSTEMS - STATUS AND REQUIREMENTS

4.1 Introduction

There is a great variety of research projects which can contribute to the advancement of the use of intelligent systems in G&C (and many other) areas [17]. These cover a broad range of activities from developments in AI to architectural and sensor improvements. A brief summary of some of these may prove useful in focusing the previous presentation.

4.2 Basic AI Research

AI-based research may prove especially useful in areas such as:

i) Sensor selection;

ii) Automatic task error detection and recovery; and,

iii) The development of high-level representations.

Neural net research will impact areas such as:

i) Object recognition through the development of distributed representations suitable for the associative recall of multisensor information; and,

ii) The development of robust multisensor systems that are able to self-organize and adapt to changing conditions (e.g., sensor failure).

4.3 At the Architectural Level

The whole guidance and control problem should be reduced to a common architectural function with the algorithmic, and intelligent software portions optimally allocated. The design of the functional requirements in such a format that allocations to the appropriate paradigms become obvious is a necessity for the evolution of truly intelligent systems.

Architectures must handle distributed intelligence with flexible control exercised where appropriate.

Of particular importance is the design of interfaces so the paradigms can exchange information and data. This is a particularly troublesome problem where the two interacting paradigms use symbolic and numeric data vectors (such as an expert system and a neural network).

4.4 Development Methodologies, Testing and Standards

There is a considerable lag between the evolution of usable software paradigms and the generation of standards for project development, management recording and testing, etc. It was many decades before algorithmic software to control mission critical activities was widely accepted. Exploiting the capabilities of AI paradigms and intelligence distributed both physically and across different paradigms is clearly a current challenge.

There is a need for the equivalent of DOD-STD-2167A and the various ISO standards [18] so that such systems can be developed, documented, tested and maintained according to a well understood set of procedures. Those who would support the utilization of new technologies would do well to support the development of such standards.

4.5 At the Sensor Level

It is clear that the continuation of the development of smart sensors will encapsulate many of the low level signal and fusion processing algorithms in on-board algorithms.

In addition it is anticipated that better signal-to-noise levels will be achievable with the built-in ability for self testing and calibration.

Low-cost integrated sensors will enable highly redundant sensors (ten times the minimal necessary) to be a routine part of a sensor array.

5.0 CONCLUSIONS

5.1 The Size of the G&C Problem

It has been estimated by Waltz and Buede [17] that the average information requirements for command and control of tactical air warfare is between 25-50 decisions/minute based on 50,000-100,000 reports from 156 separate sensors platforms concerning as many as 1000 hostile targets being tracked up to an altitude of 20 km over an area of 800 square km.

Estimates such as this suggest a massive computing requirement, and certainly, over the last few decades, computational limitations have been a serious consideration when considering G&C systems. Technology has now provided both memory and processing components - at reasonable costs - which to a large extent have moved the problem into the software area. The challenge is to utilize and exploit the capabilities of silicon technology by innovative architectures and software paradigms.

5.2 Distributed, Hybrid, Intelligent Architectures

G&C systems are and will become even more dependent on distributed hybrid intelligent architectures. Various paradigms will be instantiated at the appropriate places in the processing hierarchy according to functionality demands and capability. There are still major research problems in paradigm identification and selection, inter-paradigm communications and in the allocation of control.

5.3 Methodologies, Testing and Standards

There is a clear need for recognized methodologies for the conduct of G&C systems that are distributed hybrid and intelligent. Testing of expert systems alone is a difficult problem without the mixture of different paradigms. In the end rigid standards (a challenge to the International Standards Organization) should be in place so that confidence can be placed in the resulting system.

5.4 A Final Word on Research Directions

It is important to recognize the requirements for guidance and control in military applications is considerably different from non military applications. The key difference is the necessary assumption that the game is being played against a malevolent nature (i.e., the enemy) as distinct from a disinterested nature as in most commercial applications. This assumption converts the military guidance and control problem into a zero-sum game. Game theory is based on the assumption that at each move in the game each player selects a strategy to respond to the last move of the adversary; and associated with each move is a potential pay-off. In a zero-sum game the gain of one player is the loss of the other.

In a military situation, determining the world state vector and formulating a response must be executed on the bases that the world and possibly the sensors creating the state vector are being manipulated to maximize the system losses. The hope is that by the use of the output of multisensors that, in combination, the information can be integrated to provide an accurate representation of the state vector, whereas a single sensor could be fooled. Working against a hostile player, increases the demands on the intelligence required of the sensor fusion processing.

Military guidance and control systems will benefit directly from the advances experienced by all forms of civilian (industrial) advances in hardware and software. However, there is one area that is in general the concern only of military systems and that is the impact on sensor processing algorithms, data fusion and integration techniques, and most importantly the interpretation of the world state vector based on the assumption of an external malevolent manipulation of the world. It is suggested that research in the creation of intelligent guidance and control systems must continue to concentrate on this aspect of the overall problem.

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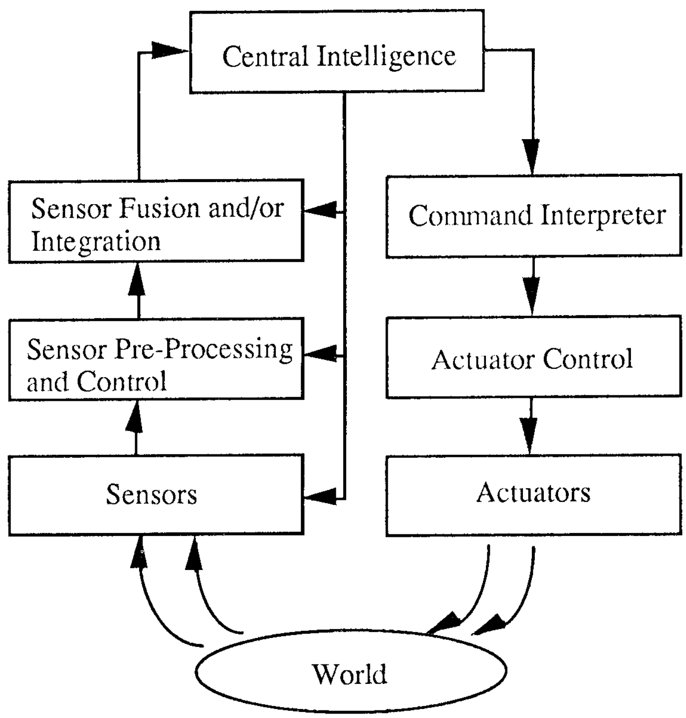
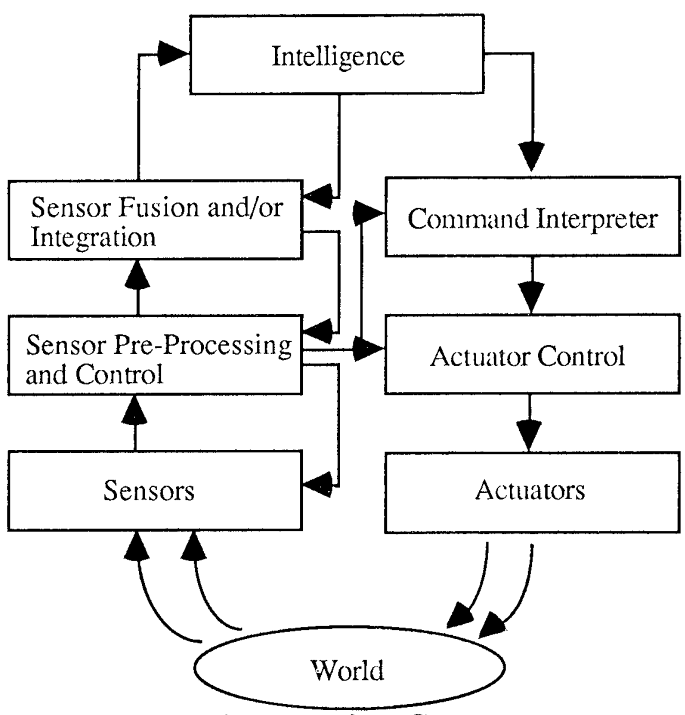


a: Centralized Control



b: Decentralized Control

Figure 1: General Logical Model of an Autonomous Robot

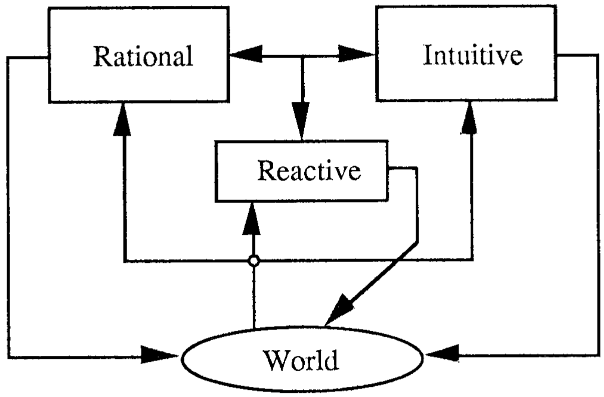


Figure 2: Functional Decomposition of Intelligent Capabilities

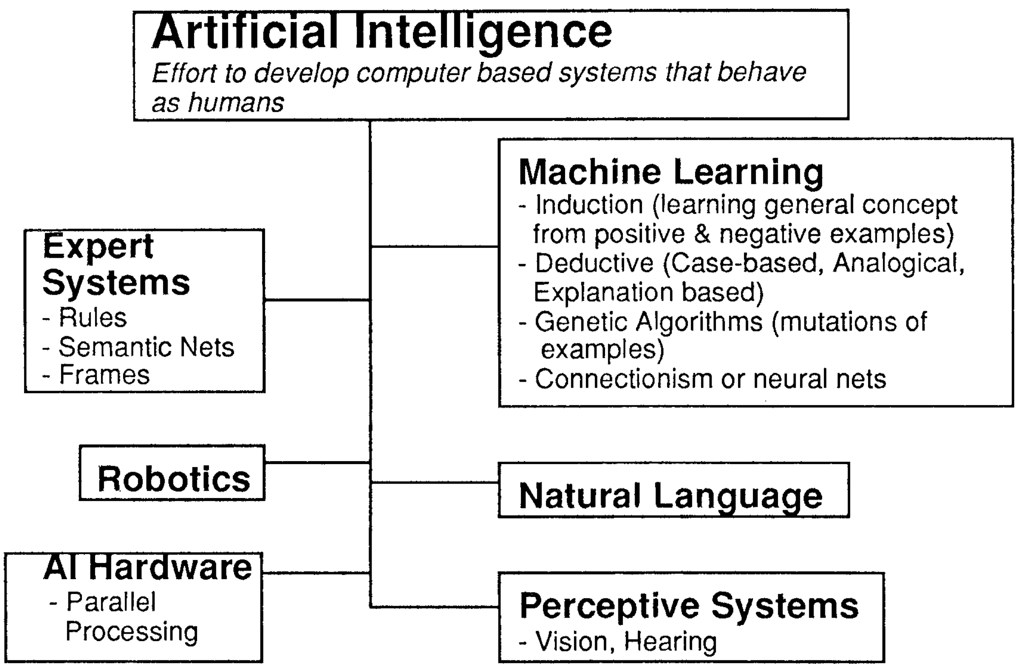


Figure 3: A View of Artificial Intelligence Paradigms

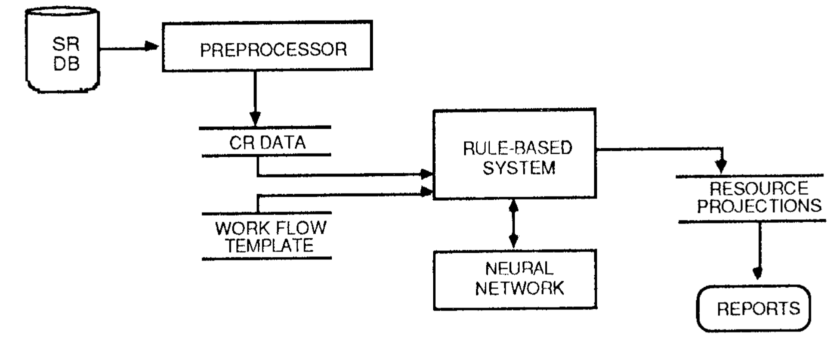


Figure 4: A Resource Projecting System

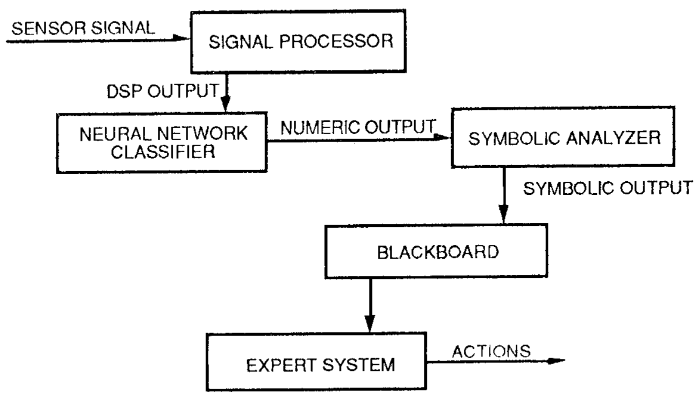


Figure 5: A Process Control System

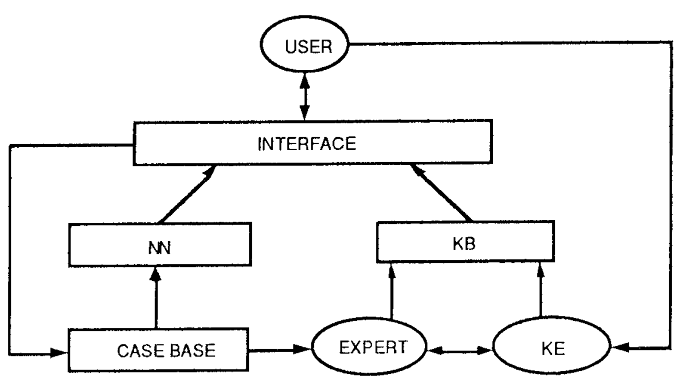


Figure 6: A Hypothesis Testing System

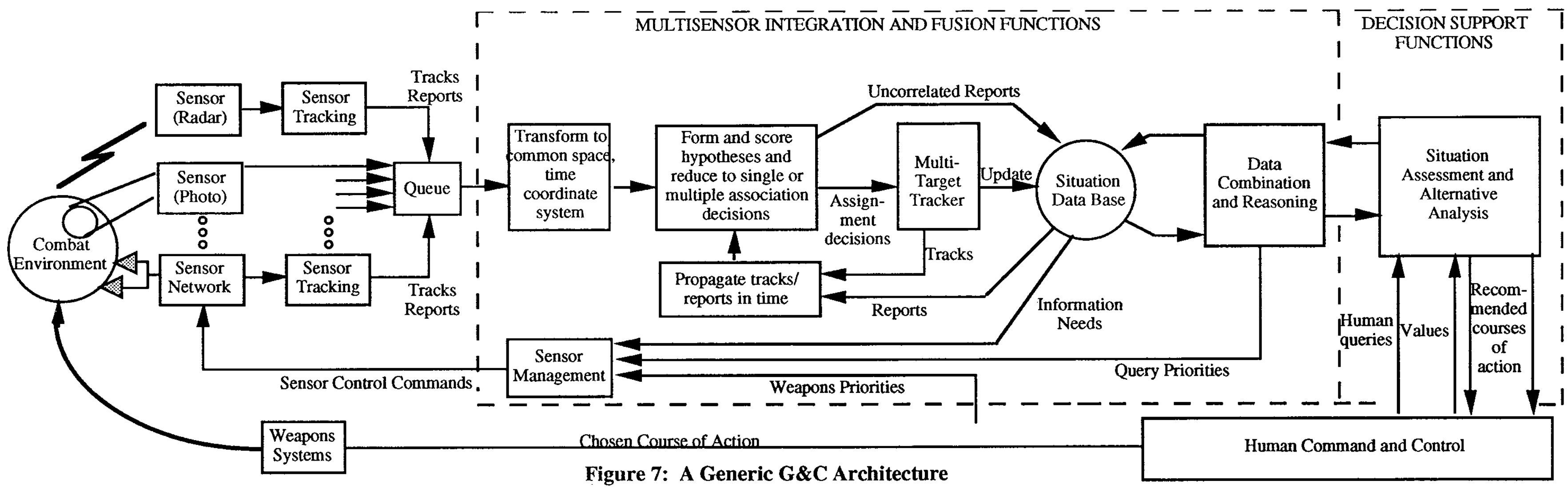


Figure 7: A Generic G&C Architecture

Control of Remotely Operated Manipulation Systems

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Abstract

Robotic systems are beginning to emerge as an effective alternative to humans for tasks that are repetitive. The next generation of space platforms, such as the international space station, will rely heavily on robotic manipulators for external servicing and maintenance. This will enhance the human presence in space and free the crew to perform those tasks that only humans can perform, thereby increasing the science return of the station.

Remotely operated manipulation systems have been accepted and widely used for the past ten to twenty years in two terrestrial applications: underwater exploration, servicing and repair; and, handling of hazardous materials in the nuclear industry. The capabilities of the systems have advanced from crude hard-wired master/slave devices, where operators are adjacent to the manipulators, to sophisticated manipulation systems that can reason at a rudimentary level, with the operators half-way around the world using telepresence in a virtual environment. To date, designing for the harsh environments and the specialized, highly skilled operators required for robotics has limited applications in the military maintenance depots and the field. Space systems, and associated ground laboratories, have advanced the manipulator technology and human-machine interface to enable a host of new cost-effective terrestrial applications in the mining, agricultural, depot maintenance, and hazardous waste cleanup fields. Integration and packaging developed for space solves the problems of robustness and tolerance to field and combat conditions. New self-contained packaging designs provide a compact system, easily used and transported. Human-machine interfaces and advanced control systems reduce the training needs and ease the turnover of skilled personnel. The day is nearby where routine tasks (such as inspection, servicing, and maintenance of equipment) will be performed by remotely operated robotic manipulators, freeing the human operator to do the diagnostics and analysis that only they can do.

This lecture will describe the elements of a remotely operated manipulation system from a requirements and technology standpoint. Particular emphasis will be placed on the system-level requirements and design drivers that are necessary for operations with humans nearby, or manipulation of delicate objects. Technology advances that enable new applications and impediments to using robotics will also be discussed. The specific elements to be discussed, and their function, are:

- *Actuators and Effectors* - ability to control and manipulate objects in the environment;
- *Sensing and Perception* - the machine's interface to the environment; provides information to the software and operator;
- *Data Management and Processing* - the computer architecture (processors and data buses that house the real-time software;
- *Control and Command Execution* - actual software algorithms that control the system and execute the task sequences; responds to operator inputs or sensing and perception data;
- *Operator Interface* - the workstation that enables the operator to interact with the manipulator; contains the hand controllers, displays, and computers;
- *Task Planning and Reasoning* - the software that enables the operator to script out and analyze situations; identifies the steps required to operate safely and accomplish the mission.

A dexterous space manipulator will be used to provide illustrative examples throughout the lecture. The manipulator is initially intended to provide the astronauts a tool to perform routine tasks in the shuttle bay such as inspection of items in the bay or worksite prepar-ation/teardown, thereby improving the astronauts efficiency during EVAs. Control techniques and the operator interface developed for this system are planned to be commercially demonstrated in an underwater servicing exercise—providing the link to the remotely operated manipulation systems that are the subject of this lecture.

Presented at an AGARD Lecture Series on 'Advanced Guidance and Control Aspects in Robotics', June 1994.

SUMMARY

Robotic systems are beginning to emerge as an effective alternative to humans for tasks that are either hazardous or routine and repetitive. Remotely operated manipulation systems have been accepted and widely used for the past ten to twenty years in two terrestrial applications: underwater exploration, servicing and repair; and, handling of hazardous materials in the nuclear industry. Technology advances have enabled new, broad space and terrestrial applications for remotely operated manipulation systems. However, in order to promulgate robotic systems further in the terrestrial work place, elements of these systems must have requirements traceable to operations with humans nearby, or manipulation of delicate objects.

A representative space-system manipulator will be used to provide an illustrative example of the evolution of remotely operated manipulation systems. The manipulator is initially intended to provide the astronauts a tool to perform routine tasks such as inspection, worksite preparation/teardown, or routine servicing and maintenance, thereby improving the astronauts efficiency during EVAs.

Emphasis is placed on the system-level requirements and design drivers. Technology advances that enable new applications, and impediments to using robotics, will also be discussed. Control techniques and the operator interface developed for this manipulator could be commercially demonstrated in an underwater servicing exercise - providing the link to the remotely operated manipulation systems that are the subject of this lecture.

1.0 INTRODUCTION

Except for the six Apollo excursions on the moon, all planetary exploration has been carried out by robotic spacecraft, albeit systems with limited capacity to act autonomously via instructions from mission controllers--a tedious task for humans. The next generation of space platforms, such as the international space station, will rely heavily on robotic manipulators for external servicing and maintenance. These systems will enhance the human presence in space and free the crew to perform those tasks that only humans can perform, thereby increasing the science return of the station. Within the next decade the development of robots that can intelligently traverse large distances, observe the terrain, manipulate and analyze samples, service and maintain equipment, and report findings back will be feasible.

Currently, remotely controlled (teleoperated) and semi-autonomous systems with manipulation and mobility exist in laboratories and, to a certain extent, in industry. The undersea oil and nuclear power industries have been using intelligent, or teleoperated manipulators for the past two decades. Successes in space with the Space Shuttle Remote Manipulator System (RMS)--witness the Hubble repair mission--have spurred additional technology development. The capabilities of the systems have advanced from crude hard-wired master/slave devices, where operators are adjacent to the manipulators, to sophisticated manipulation systems that can reason at a rudimentary level, with the operators half-way around the world using telepresence in a virtual environment.

Nevertheless, designing for the harsh environments and the specialized, highly skilled operators required for robotics has limited applications in space, the military maintenance depots and the field. Space systems, and associated ground laboratories, have advanced the manipulator technology and human-machine interface to enable a host of new cost-effective terrestrial applications in the mining, agricultural, depot maintenance, and hazardous waste cleanup fields. Integration and packaging developed for space solves the problems of robustness and tolerance to field and combat

conditions. New self-contained packaging designs provide a compact system, easily used and transported. Human-machine interfaces and advanced control systems reduce the training needs and ease the turnover of skilled personnel. The day is nearby where routine tasks (such as inspection, servicing, and maintenance of equipment) will be performed by remotely operated robotic manipulators, freeing the human operator to do the diagnostics and analysis that only they can do.

Exhibit 1-1 provides the topics for the remaining section of this report. Exhibit 1-2 illustrates trends in the development and maturity of remotely operated manipulators.

2.0 SYSTEM DESCRIPTION

It is useful to decompose a Remotely Operated Manipulation System into functional elements for discussion purposes. For the purpose of this discussion the elements, and their function, are:

- *Actuators and Effectors* - ability to control and manipulate objects in the environment;
- *Sensing and Perception* - the machine's interface to the environment; provides information to the software and operator;
- *Data Management and Processing* - the computer architecture (processors and data buses that house the real-time software;
- *Control and Command Execution* - actual software algorithms that control the system and execute the task sequences; responds to operator inputs or sensing and perception data;
- *Operator Interface* - the workstation that enables the operator to interact with the manipulator; contains the hand controllers, displays, and computers;
- *Task Planning and Reasoning* - the software that enables the operator to script out and analyze situations; identifies the steps required to operate safely and accomplish the mission.

These elements and their physical implementation are shown in Exhibits 2-1 and 2-2; internal and external support needs are listed in Exhibit 2-3.

One must first understand the underlying requirements that drive a robotic system. The next section, 2.1--System Requirements and Design Criteria--will discuss those requirements, and the associated design criteria, which form the basis for a remotely operated manipulator. Following that discussion will be a description of the physical components that make up a robotic system. System Design Elements, Section 2.2, focuses on those design elements that control a robotic system. Control issues associated with remotely operated manipulators are highlighted in Section 2.3, System Control and the Operator Interface.

2.1 System Requirements and Design Criteria

The approach used to develop the requirements for a robotic system is an iterative one which relies on a definition of the tasks required to be performed by the system. Knowledge of the task definition, resources available, worksite constraints, etc., are essential to avoid over-specification of requirements. Parallel emphasis needs to be placed on the state of the technology base to ensure that technology development and validation plans are in place to support the program. As systems are fielded, operational lessons learned and new technology needs can be fed back into the robotic development effort.

The optimal definition of a robotic system (manipulator kinematics, mobility, operator interface, etc.) stems from a task analysis to avoid specification of unneeded capabilities or features. An understanding of the task requirements (worksite constraints, task element characteristics, sequence of operations) leads to kinematic and dynamic simulation that develops the manipulator configuration, vision system requirements, and collision avoidance requirements. Additionally, the robotic system duty cycles, which drive the host platform resource requirements, are directly related to the task sequence of events. Exhibit 2-4 portrays the task-driven methodology.

It is critical to establish a complete set of detailed system and lower-level specifications early in the program, well before hardware design is initiated. Realistic margins must be established in the requirements, to allow for unplanned contingencies as the design progresses. Of

equal importance at this time in the program is to plan ahead for verification of the requirements--all requirements should be established in the form of quantifiable, verifiable specifics. The appropriate level of requirements traceability must be clearly established, with concurrence from the developing agency and user communities.

Establishing the overall system performance, based on a specific mission simulation, is critical in establishing requirements flow-down and allocation to lower-level subsystems and hardware. Key performance requirements are listed in Exhibit 2-5. For a robot, the manipulator and its required performance, are the key to ensuring mission success. Realistic force/torque requirements at the interface between the manipulator and the work piece need to be set to enable the manipulator to perform all its assigned tasks. The kinematics of the manipulator and the relationship with the worksite must be considered, with respect to force/torque and also to power. Realistic margins on both minimum and maximum performance should be set up that will allow the manipulator to perform its assigned tasks, but yet consider power and safety implications. While minimum requirements ensure that the manipulator can perform its tasks, maximum requirements help limit loads on the manipulator and the end effector, and on all work pieces with which it comes in contact. In addition to placing requirements on static forces and torques, considerations should also be given to specifying joint and Cartesian velocities and accelerations. Exhibit 2.6 summarizes the considerations for establishing system-level performance force/torque requirements.

One of the key drivers affecting the design of remotely operated manipulators, when a human or fragile/expensive equipment is nearby, is the safety requirements. Exhibit 2-7 provides a correlation of the safety requirement for a dexterous space manipulator and resultant design impact. Safety needs to be addressed early in the development cycle as it has major impacts on the system architecture and associated hardware and software design. These are among the first set of requirements that must be established and frozen. Past robotic systems in terrestrial and space applications have suffered from the lack of understanding of the safety issues. After the system is built and fielded, the only recourse to a safety inadequacy is to limit the operations of the manipulator, and hence its utility.

Some of the important worksite interface considerations used in manipulator design are discussed in Exhibit 2-8. All of these items should be considered very early in the design, and re-evaluated for impacts whenever design changes are considered. The kinematic analyses are performed on a simulator model that later can be integrated into the operator workstation for task planning and preview. This model is used to evaluate manipulator dexterity, viewing requirements, work piece locations, and viewing/guiding aids. In addition to the computer simulations, lab tests using realistic hardware also are essential to help establish performance requirements and to evaluate the design. The criticality of the usage of these tools in establishing and optimizing human-machine interfaces, and in establishing and evaluating detailed requirements and performance capabilities cannot be over-emphasized.

When designing elements for robotic servicing, one must keep in mind that all manipulators have a preferred work area which maximizes their dexterity. Dexterity requirements are dependent on the tasks performed. A single grasp point, with a nut runner interface and straight line removal is preferable from a robotics standpoint. Dexterity is then directly proportional to the removal distance. Another constraint placed on a designer by robot servicing is clearance envelopes. There is a minimum diameter about the grasp point required by EVA standards. For robotic servicing one must also consider visual clearance envelope to allow the camera to "see" the alignment cues. Exhibit 2-9 illustrates design concepts for robotic compatibility.

Human-machine interface considerations should be used extensively throughout the system development. They are used to evaluate the interaction between the human operator and environment and in layout and operation of the workstation. A key tool is a prototype simulator to develop and evaluate the hardware and software required for displays and controls. Critical to the design and acceptance of robots

is the early involvement of the end users. This permits that lessons learned from previous experience can be input early in the design, gives the system designers and system users the chance to interact, and ensures vital support from the people that will use the hardware in operations. Key considerations are reiterated in Exhibit 2-10.

Do not forget to determine the data the operators and logistics support team need to check out the system, determine the performance of the system, and diagnose anomalies. Date content and rate can impact the software design and processor architecture. Refer to Exhibit 2-11 for a data checklist.

2.2 System Design Elements

The functional elements of any remotely operated manipulation systems were defined in Section 2.0, with an illustrative physical manifestation portrayed in Exhibit 2-2 (a dexterous space manipulator). Focus in this section will be on the three main components of the system, which embody all six functions: 1) the Manipulator, 2) the Command and Data Processing System, and 3) the Operator Workstation.

An example of a dexterous manipulator is shown in Exhibit 2-12. Key characteristics of the manipulator are listed in Exhibit 2-13. In this example, a portion of the Command and Data Processing System is imbedded in the arm links. This manipulator is a robotic arm with seven degrees of freedom. The joints are configured to provide a closed-form inverse kinematic solution and in such a way that the manipulator has singularities only at limits of travel. The manipulator is comprised of several smaller subsystems: actuators, force torque transducer, end-of-arm tooling, vision system, and electronic controllers. All structural members are designed to provide required stiffness to achieve minimum bandwidth frequency under active control. It is designed to be reconfigurable to either a right- or left-handed configuration on adjustment of the shoulder yaw hardstops. Key performance requirements are defined as forces, torques, and speeds that the end of the arm must achieve under worst case conditions.

The manipulator is powered by regulated 120 volts and controlled through distributed electronics located in the shoulder, upper arm, and lower arm links. A 1553 data bus and video signals are routed throughout the arm and up to the tool plate. An electrical secondary path is provided to operate the manipulator in a degraded mode as required to complete a mission or store the arm in case of a failure in the primary control system. A thermal control system is utilized to maintain acceptable electronic part temperatures in the controllers and actuators. The actuators have a manual release mechanism that allows a human to release a jammed actuator and manually backdrive a joint for stowage.

The manipulator joint actuator provides the positioning capability for the manipulator and the torque required to generate forces and torques at the manipulator tool plate. The actuators are designed to produce the required manipulator performance in the primary control operations mode, as well as degraded performance in a secondary mode. They also electrically link the distributed controllers and other subsystems together along the manipulator arm.

Each actuator typically includes a motor, transmission, output position sensor, output torque sensor, fail-safe input brake, hardstops, temperature sensors, and a flexible cable wrap. The shoulder roll actuator may also have a brake at its output. Housings are designed to provide required stiffness to achieve the minimum bandwidth frequency of the manipulator under active control.

The conductor cable allows power, signal and balanced lines to be routed to and through each actuator while allowing freedom of motion and minimum disturbance torque. Each cable is uniquely configured to fit within an actuator and allow proper joint rotation while providing static interface connections between actuators or controllers.

A sensor measures the joint position. This joint position is then supplied to the data management and processing system as inputs to the control system and for safety checks to prevent a "runaway" manipulator.

Vision and tactile sensing are the major senses involved in manipulation. Examples of different alternatives to provide these sensors is contained in Exhibit 2-14.

The wrist camera provides a close-up view of the task being performed, and typically the field-of-view includes a portion of the end effector for relative orientation. Lighting can be included to provide uniform illumination of the task area--a requirement for some image processing systems.

The Force/Torque Transducer at the end effector interface to the arm provides data in six degrees of freedom (three forces, three moments) when in contact. This data is used for control of the manipulator as well as safety for prevention of excessive force.

There are two distinct means to use the force and torque data for control. In the first case data can be provided to the operator at a workstation equipped with a force-reflected hand controller. This is most useful in teleoperation where the operator physically "feels" the force exerted on the worksite. The alternative to this approach is to use limits set in software to autonomously adjust the amount of force applied to the worksite. This is a type of control known as compliant control or force-moment accommodation. Visual aids and graphics can be supplied to the operator for supervisory tasks.

2.3 System Control and the Operator Interface

Robots with multiple degree-of-freedom (DOF) manipulators are very complex machines to control. There is constant concern with the location of objects in three-dimensional space. These objects are the manipulator links, the end-effectors and tools, and elements of the work space. Location of these objects is described by their position and their orientation. The goal of manipulator control is to place the end-effector at the position of the work piece to be manipulated with a relative orientation that will provide the required dexterity to accomplish the task.

A few definitions, listed in Exhibit 2-15, are in order before proceeding further in the discussion of control. Kinematics is the science of motion without regard to the forces which cause the motion. The existence of a kinematic solution defines the work space of the manipulator. The manipulator inverse kinematics, a nonlinear problem, are the key to position control of the end-effector.

The manipulator is a series of nearly rigid links which are connected by joints to allow relative link motion. The joints are either revolute (rotary) or prismatic (extending). These links and joints form a kinematic chain with the free end being the end-effector. When in contact and grasping the work piece, the open kinematic chain becomes closed, and the dynamic equations governing control are altered - increasing the complexity of control.

With this background in hand, there are several major trades that shape the control system design; these trades are summarized in Exhibit 2-16. The two ends of the spectrum for operator control are: 1) Teleoperated, or guided by a human on a continual basis at low or high levels and from some distance with possible time lag; and 2) Supervisory Control where automated robots carry out a specified set of pre-programmed functions and robots with a higher degree of autonomy actually respond to new situations with little or no additional guidance from the operator.

Key to the successful completion of any teleoperated robotic task is the environment with which the robot needs to interact. A well-defined environment (minimum clutter and precisely defined in the model of the world) reduces the amount of intelligence required to accomplish the task. In a teleoperated scenario, the operator is in the control loop and uses his own senses/intelligence to understand the environment, manipulate objects, and close the feedback loop.

Under supervisory control, the operator must divide time between monitoring the systems performance and giving commands to the computer. Monitoring is a stochastic process and can only predict that an event will occur, but cannot predict the time or place. This stochastic nature forces the operator to maintain a constant vigilance on the system's operations.

The location of the operator relative to the robot is an important aspect of any robotic system architecture. When the operator and robot are separated by a large distance (e.g., robot in low earth orbit and operator on the ground), communication delays can be a significant factor in system design. A large delay implies that special compensating measures such as increased automation, predictive displays, or sensor-based collision avoidance need to be incorporated. On the other hand, small distances between robot and operator (e.g., operator and robot located contiguously), implies increased utility of teleoperation and capabilities such as force reflection.

Furthermore, the separation distance between robot and operator affects contingency planning and task viewing. When the operator is collocated with the robot, it may mean that human operations are possible to assure task performance under contingencies. When human backup is not possible, extra redundancy and operational margins may be necessary in the robot system to achieve the desired probability of success for critical tasks. Also, when the operator location permits direct viewing of the robot task, there is a reduced need for camera views and workstation monitors.

Once a decision is reached on the degree of operator involvement, a partitioning of functions between the "local" operator site and "remote" robotic worksite is defined. The driver to partitioning functions between local and remote sites is to make the system less sensitive to issues such as intermittent communications, time delays, and communication bus latencies--all of which tend to be destabilizing. A sample partitioning of functions is shown in Exhibit 2-17.

The controls algorithms provide the means for the robotic hardware to accomplish its intended performance. A sample dexterous space manipulator control architecture is depicted in Exhibit 2-18. There is an "inner" torque loop that precludes the application of excessive force at the worksite. A Cartesian position loop then compares the sensed actual position to the commanded position and orders appropriate motion. Finally, the outermost loop provides force feedback to the operator so that teleoperation can be accomplished with a sense of "feel." This promotes dexterous operations required for fine manipulation of objects. The partitioning of functions between the operator workstation (local) and manipulator (remote) is further magnified in Exhibit 2-19.

A key feature of the controls algorithms includes 6-DOF active control with the seventh shoulder roll joint operated in an indexing mode to control the placement of the elbow (i.e., elbow up, elbow down, or selectable anywhere in between). The seventh joint could be included actively in the control algorithm to form a redundant control architecture. The controls algorithms permit the system to be operated via teleoperation, or in an autonomous mode, with selectable levels of force reflection available in the teleoperated mode, and selectable levels of impedance control available in both teleoperations and autonomous control. The functional requirements for the control system are listed in Exhibit 2-20. Some of the key controls issues include contact stability, contact force spikes, impedance control, inertia decoupling and force reflection.

The control algorithms must be specified using a standard. One option for guidance is the NASA/NIST Standard Reference Model for Robotic Systems (NASREM), portrayed in Exhibit 2-21. The control algorithms discussed previously concentrated on the servo and primitive levels.

The servo level incorporates all real-time processing required to meet the control loop timing requirements. The servo level is subdivided into workstation and telerobot algorithms. The data interfaces for the servo level can be characterized as follows:

- *Hand Controller to Workstation Algorithms* — sensed hand controller joint positions;
- *Workstation to Telerobot Algorithms* — commanded (teleoperated) object velocities;
- *Telerobot Algorithms to Telerobot Manipulator* — commanded actuator currents;
- *Telerobot Manipulator to Telerobot Algorithms* — sensed tool plate forces and torques;

- *Telerobot to Workstation Algorithms* — sensed (teleoperated) object forces and torques;
- *Workstation Algorithms to Hand Controller* — commanded actuator currents.

The primitive level incorporates all processing required to define, execute and monitor path planning between way points in either Cartesian or joint space. The primitive level passes position commands (either Cartesian or joint) to the servo level at the servo level control rate, and monitors exception conditions to define error conditions.

The operator workstation is the human-machine interface for the robotic system. For a given robotic system, the only difference between ground-based workstations is the operator's "chair." The common interface devices provide input, feedback, and monitor functions. The balance between teleoperation and autonomy for the specific robotic system determines the character and requirements of these interface devices. The very nature of teleoperation requires hand controllers as input devices. A fully autonomous system might use only a keyboard and a mouse for input devices. The amount and form of feedback from the sensors in the system is a function of the types of tasks to be performed and system considerations. For example, force feedback to the hand controller aids teleoperation during fine dexterous manipulation.

In order for the robot operator to monitor task performance, the state of the work space, and the state of the robot, data must be transmitted from the robot to the operator workstation. Likewise, data transfer from the workstation to the robot is necessary to allow the operator to issue commands that control robot functions. Data exchange is accomplished in one of two ways: hardwire connection or RF link between robot and operator. Hardwire data exchange, which includes fiber optic links, has the advantage of high bandwidth that readily accommodates transmission of multiple video channels and force feedback data. RF links allow data exchange over large distances such as low earth orbit to ground, but are often bandwidth-limited.

Lastly, to accomplish the task efficiently not only requires the right robotic system for the task, but requires a fully trained operator well versed in the system and task at hand. Simulators and kinematically correct trainers can reduce task times by a factor of 1.5 to 3, which is significant when performing servicing and maintenance operations.

3.0 APPLICATIONS

Extending the useful life of operational systems via maintenance, assembly, and repair requires dexterous manipulation. Future proposed missions envision a dexterous manipulation environment that is more hazardous, remote, and extensive than the current mission scenarios. In this hostile environment an intelligent system that is capable of dexterous manipulation would enhance or, in some cases, be critical to mission success. Examples of potential applications are contained in Exhibit 3-1.

The following section, 3.1, discusses some potential uses for remotely operated manipulators. In Section 3.2 a questionnaire is provided to help understand issues associated with selecting robotic systems.

3.1 Current and Future Uses

Teleoperated robots are designed to extend human's presence in hazardous environments such as nuclear radiation, high temperature applications such as burning buildings, undersea operations at tremendously high pressure (extreme depths), and the harsh space environment. These environments limit human's performance and can endanger life. Teleoperated systems are implemented because of their lower cost and maturity in fielding a working system. Ease of implementation to an untrained operator reduces cost and can be a time saving advantage to everyday operations. There are some current successes using remotely operated systems.

The nuclear power industry has made significant use of glove boxes, manipulators and mobile robots for work in high-radiation environments. In the mid-1980s, cleanup of the Three-mile Island power plant in Pennsylvania was accomplished with mobile,

teleoperated robots equipped with tools for inspection, cutting, drilling, and welding.

The undersea oil industry has used ROVs equipped with manipulators to inspect oil rigs on the sea floor and pipelines for weld integrity. The National Science Foundation, in conjunction with NASA, is furthering undersea use with an advanced human-machine interface -- Telepresence -- in Antarctica.

In industry, a tiny constrained niche exists for robots performing fix-based manipulation in highly structured tasks with only operator supervision. This is used extensively in pharmaceutical and assembly-line manufacturing.

Broader use of robotics is hampered in many areas because of technology or system limitations. Many of these limita-tions are being eliminated by new ways of integrating and packaging robotics.

Reliability, fault tolerance, and safety features of space manipulators can be transferred to increase the use of robotics in handling, manufacturing, and testing of extremely high-value hardware. There are many areas that would see increased profits and availability if they could be built using batch processes, eliminating expensive and slow custom building. The totally integrated operational hierarchical control system discussed earlier will pave the way for advanced path and task planning, thus allowing cost-effective use of robotics in low-volume manufacturing.

Robotics in hazardous areas such as nuclear reactor maintenance need to be teleoperated. Teleoperated robots lower the risk to people and allow more efficient operations or clean-ups. Higher levels of control allow pure teleoperation, supervised autonomy, or completely automated control. These features reduce the need for highly skilled operators and reduce operator fatigue. Increased effectiveness and better use of our small population of highly skilled operators make robotic benefits vital in the areas of fire fighting, asbestos removal, pollution cleanup, and other hazards.

The harsh environments and specialized, skilled operators required for robotics in maintenance depots or the field have until now limited robotics in the military. Integration and packaging developed for space solves the problems of robustness and tolerance to field and combat conditions that had limited robotics use by our armed forces. The self-contained packaging concept provides a compact system, easily used and transported. New human-machine interfaces and advanced control system reduce the training needed and eases the turnover of skilled personnel.

Currently robotics are extensively used in underwater exploration and servicing. However, much like hazardous environment maintenance, undersea exploration and servicing needs more than predominantly pure teleoperation offered by current robotics. Compact electronics packaging allows extensive onboard capability, reducing reliance on unwieldy umbilicals and more flexibility than pure master-slave control.

Ongoing program development activities have direct applicability for lunar and planetary exploration. Use of already space-qualified robotic components would reduce the costs for future systems. The supervised autonomy and high-level autonomous control architecture will allow better mission control, as the current pure teleoperation suffers from long communication time delays. A self-contained compact computer architecture provides the computational resources required for these missions.

The development of on-orbit satellite servicing has been shown to be highly cost effective. Required technologies can be directly transferred from existing research including manipulators, data system, control system, vision, sensors, and power. The flight-development status of these technologies will significantly shorten the development time and cost of satellite servicing systems.

Current technology restricts the use of robotics in applications such as agriculture, construction, and warehouse operations. The integration of robotic technologies and the compact packaging discussed here provide a blueprint for similar commercial implementations. The high reliability, safety, extensive integrated

computing capability, and human-machine interface features address the most critical obstacles limiting robotics use in these areas. Cost-effective robotic products for these areas increase efficiency and productivity.

3.2 Application Questionnaire

The following series of questions help to define the selection of the proper robotic system for a given application.

Understanding the Environment

- What type of operations or activities characterize your industry or field?
  - Any tasks currently performed by machines (pick and place, NC, operator controlled, etc.)?
  - Any repetitive tasks?
  - Any time-intensive tasks?
  - Any tasks hazardous to humans?
- What characterizes the environment?
  - Is it clean or dirty (particulates, radiation, moisture, etc.)?
  - What is the gravity (on Earth--1g, in space--0g, on a planet, moon, etc.)?
  - What is the pressure (ambient, space, undersea, etc.)?
- What are the constraints and limitations placed on personnel and machines in the work space?
  - Are there weight limits (floor loads, transport to/from limits, etc.)?
  - Are there volumetric constraints (width/height of corridors, clear volume in work cell, etc.)?
  - Are there obstructions to work around?
  - Is there clear visibility of the task being performed?

Understanding the Task

- What are the characteristics of the work space?
  - Does it contain rigid, structured, unchanging work cells capable of being accurately modeled a priori?
  - Are there areas that are unstructured and changing that require real-time knowledge of the work space?
- What are the attributes of the tasks being performed?
  - Is contact required (stiff, soft, variable stiffness)?
  - Is precise position or velocity control needed?
  - Is base motion required?
  - Is sensory interpretation required (visual analysis, gas detection, etc.)?
- Does it require manipulating objects?
  - Are they attached or in free space?
  - Do they have variable mass and inertia;
  - Any offset CGs?
  - Is the grasp point designed for robotics (standard interface, special tool, etc.)?
- Are there safety considerations involved?
  - Is inadvertent release of objects or tools a concern (damage to the object, damage to surroundings, etc.)?
  - Is excessive force or contact a concern (breakage, deformation, etc.)?
  - Does a runaway manipulator cause concern (injury to humans, damage to environment, damage to manipulator, etc.)?

Understanding the Operator Interface

- If robotics are currently in use, what is the operator involvement?
  - Is it real-time control of the device or supervision?
  - Is the operator located locally or remotely?
  - What are the operator inputs to/from the machine (to-high-level task commands, hand controllers, etc.; from-visual, force feedback, graphical, etc.)?
- What are the operator desires?
  - Do they want direct control, supervisory responsibilities, or a mix?
  - If it's a manipulator, do they want single joint control, joysticks, master/slave, or some other kinematic mapping of commands?
  - How does the operator envision the workstation to look (portable box with joystick and knobs, sophisticated displays and processor interfaces and hand controllers, etc.)?
  - Should the workstation be located nearby, with direct line-of-sight?
  - What feedback is desired (camera views and how many, force feedback, graphical overlays, etc.)?
- How will communications occur with the workstation?
  - Will there be hard-lines, or wireless (any limitations)?
  - Is it digital, analog, or some combination?

Understanding the Requirements

- What are the characteristics of the machine needed?
  - Actuators and Effectors (mobility of device, movement/control of objects, DOFs, etc.)?
  - Sensing and Perception (machine interface to environment - cameras, force/torque transducers, etc.)?
  - Data Management and Processing (processor architecture, data buses, etc.)?
  - Control and Command Execution (type of control--position, rate, force, Cartesian, joint, etc., partitioning of local/remote control, command authority)?
  - Operator Interfaces (hand controllers, displays, graphics, software, etc.)?
  - Task Planning and Reasoning (task sequence development, situation analysis and reasoning, replanning, etc.)?
- What are impediments to using robotics?
  - Is it lack of knowledge or understanding?
  - Is it the implementation costs?
  - Do you need training?
    Is new technology required?
- What are the enablers for using robotics?
  - Does it require a proof-of-concept elsewhere?
  - Does it need to have a minimal up-front cost to implement?
  - Does the system need to be robust?
  - Is new technology required (operator interface, AI/reasoning, improved effectors, etc.)?

4.0 SUMMARY AND CONCLUSIONS

Robots fall short in areas where humans excel--those that require a broad experienced data base and the ability to link disparate, unexpected observations in the field. Tenets professing this philosophy are listed in Exhibit 4-1. These tenets have shaped the robotics industry to date in terms of the niche robots occupy and the associated implied capabilities and limitations.

Three of the most important areas of research to increase robotics applications by providing humans with greater capability (listed in Exhibit 4-2) are : 1) more autonomy in robotic systems, 2) greater mobility and capacity for dexterous manipulation, and 3) advances in the human-machine interface. Humans can then guide at any level of control from tele-operation to supervised autonomy, and from both short and long distances. More effective robotics will leave humans free to reason and control at the most effective level for discovery.

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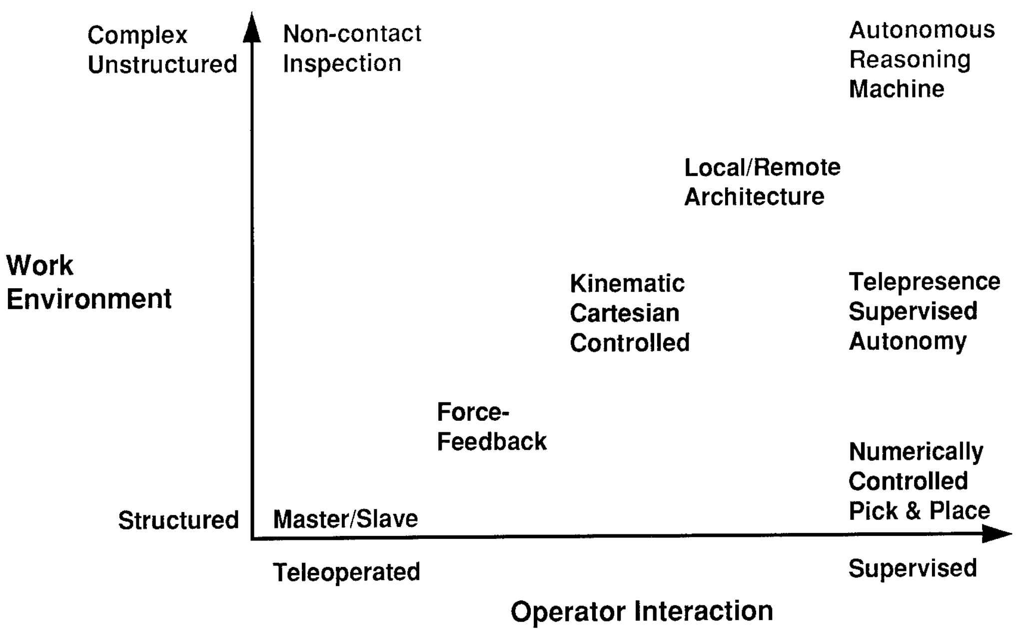
Exhibit 1-1: Topics

- Introduction
- System Nomenclature
- System Requirements and Design Criteria
- System Design Elements
- System Control and the Operator Interface
- Applications
- Summary and Conclusion

Exhibit 1-2: Robotic System Trends



Robotic Systems Are Evolving from Crude Master/Slave Devices to Sophisticated Reasoning Machines with Remote Operator Telepresence

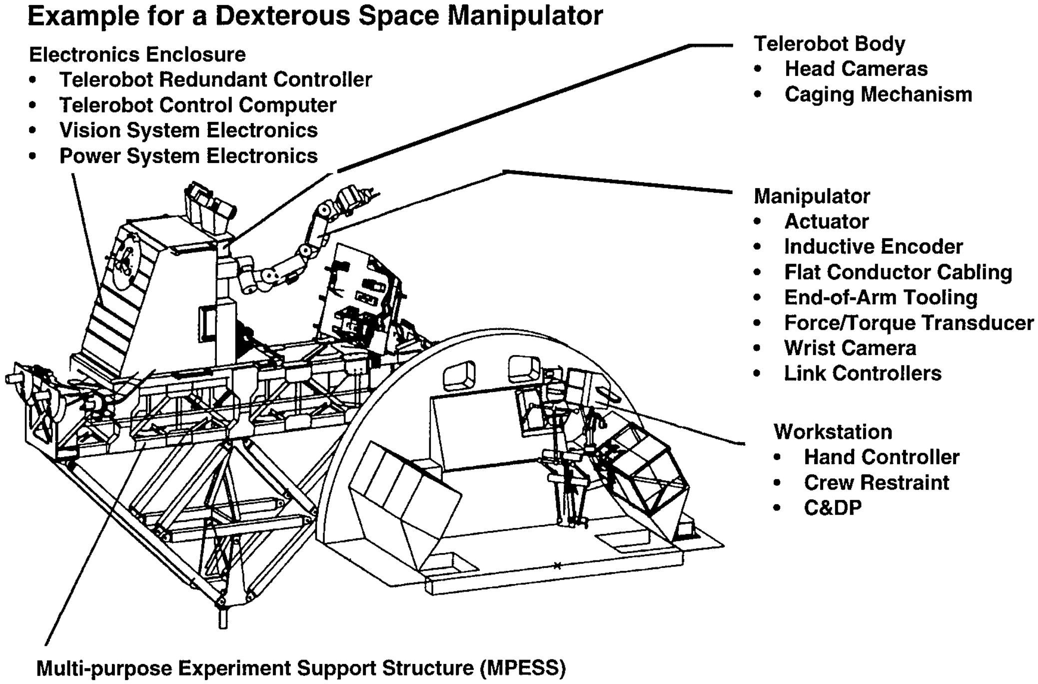
Exhibit 2-1: Manipulator System Functional Decomposition

Element	Function
Actuators and Effectors	Ability to Control and Manipulate Objects in the Environment
Sensing and Perception	Machine's Interface to the Environment; Provides Information to Software and Operator
Data Management and Processing	Computer Architecture; Processors and Data Buses That House Real-time Software
Control and Command Execution	Software Algorithms That Control the System and Execute Task Sequences; Responds to Operator Inputs or Sensing and Perception Data
Operator Interface	Workstation That Enables Operator to Interact with Manipulator; Contains Hand Controllers Displays and Computers
Task Planning and Reasoning	Software That Enables Operator to Script Out and Analyze Situations; Identifies Steps Required to Operate Safely and Accomplish Mission

Major Functions Required for Remotely Operated Manipulation Systems Are Traceable to Their Human Counterpart

Exhibit 2-2: Manipulator System Components

Example for a Dexterous Space Manipulator



Remotely Operated Manipulation Systems Are Composed of the Robot Itself and the Operator's Workstation for Controlling the Robot

Exhibit 2-3: Robotic System Needs

External

- Operations
  - —Remote
  - —Local
- Power
  - —Batteries
  - —Host Vehicle
- Mobility to and from Worksite
  - —External to Robotic System
  - —Integrated into Robotic System
- Data Exchange (Data & Video)
  - —Hardline
  - —RF System
- Stability at Worksite
- Operator Workstation
  - —Hand Controller(s)
  - —Monitors and I/O Interface
- User Interface
  - —Human
  - —Robotic

Internal

- Data Processing
  - —Internal to Robot
  - —External to Robot
- End Effectors
  - —Gripper and Tools
  - —Articulated Hand and Tools
- Manipulator(s)
  - —Number and DOF
  - —Actuators and Cabling
- Thermal Control
  - —Passive
  - —Active
- Sensors
  - —Video
  - —Force - Torque
- Controls
  - —Force Reflection or Feedback
  - —Impedance/Compliance
  - —Position (Cartesian) or Rate

All Robotic Systems Have Basic Support Needs Dependent on Their Configuration

Exhibit 2-4: Task-driven Methodology

Task Descriptions

- Motion Requirements
  - — Straight Line
  - — Curved
  - — Rotations
  - — Distance
  - — Precision
- Task Element Features
  - — Mass
  - — Volume
  - — Grasping Interfaces
  - — Tool Interfaces
- Worksite Characteristics
  - — Clearances
  - — Stiffness

Task Analysis

- Kinematic Simulations
  - — Manipulator DOFs
  - — Number of Arms
  - — Body Positioning
- Vision System
  - — Number of Cameras
  - — Number of Monitors
  - — Lighting Requirements
- Forces and Torques
  - — Sensing Requirements
  - — Actuator Sizes
- Collision Avoidance
  - — Safe Zones
  - — Clearances

Robotic System Definition

- Manipulator(s) Features
  - — Size and DOFs
  - — Strength and Dexterity
  - — Control Methodology
- Mobility Implementation
  - — "Body" Configuration
  - — Support Systems
- HW/SW Architecture
  - — Processing Reqmts
- Human/Machine Interface
  - — Location
  - — Sensory Feedback
  - — Complexity
  - — Level of Autonomy

Use a Task-driven Methodology to Specify the Robotic System

Exhibit 2-5: Key Performance Requirements

Example for a Dexterous Space Manipulator

Requirement	Value
Accuracy	1 in., 3 deg (Autonomous Tasks Value 1/4-1/2 of Spec.)
Repeatability	0.1 in., 0.25 deg (or Human Equivalency) 0.005 in., 0.05 deg (for NC Machines)
Incremental Motion	1/5th the Value of Repeatability
Tip Force/Torque at Toolplate	20 lb Minimum Force in Any Direction 20 ft-lb Minimum Torque
Translation Rate at Toolplate, Fully Extended	24 in./sec Minimum (No Load) 6 in./sec Minimum (90 lb Load)
Dexterity	7 DOF for Multiple Poses/Task $\pm$ 90 deg Wrist Pitch/Yaw, $\pm$ 360 deg Wrist Roll Dexterous Work Space 4-6 ft from Base of Manipulator

Derive a Basis for Performance Requirements Using Expected Tasks

Exhibit 2-6: Requirements Considerations

System Performance Requirements

- Derive a Basis for Accuracy, Repeatability and Incremental Motion Based on Expected Tasks
- Define in a Quantitative Manner the Response of the System from an Operator's Standpoint
- Base Requirements Flow-down and Allocation on System Performance Simulations

Manipulator Force/Torque Requirements

- Establish Realistic Force/Torque Requirements Early Based on Expected Tasks
- Understand How Manipulator Kinematics Affect Force, Torque and Power
- Define Point of Force/Torque Application and Where Forces and Torques are Measured
- Understand Worksite Range and Locations at Which Force/Torque Requirements Are Set
- Establish Realistic Margins, Not Just Minimum Requirements and Understand Maximum Capability Impacts on Safety

The Manipulator's Required Performance Is the Key to Ensuring Mission Success

Exhibit 2-7: Safety Requirements

Example for a Dexterous Space Manipulator

Safety Requirement	Ramification
Two-fault Tolerance for Safing System	• Addition of Backup Modes/Separate Paths for Operations
Two-fault Tolerance to Inadvertent Release of Hardware	• Increased Size and Complexity of End Effector • Additional Complexity in Commanding • Dedicated Interface Design for Releasable Hardware
Two-fault Tolerance to Unplanned Contact with the Environment	• Addition of a Boundary Management System • Multiple Checks on Manipulator Joints in Hardware and Software
Two-fault Tolerance to Applying Excessive Force/Torque to Worksite during Planned Contact	• Addition of Emergency Shutdown System • Multiple Paths in Hardware and Software • Additional Processors, Wiring and Sensors

The Single Largest Factor Driving System Design is Safety

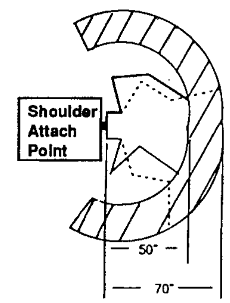
Exhibit 2-8: Worksite Interface Considerations

Worksite Interface Considerations

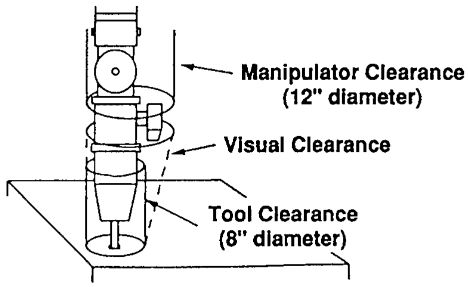
- Perform Kinematic Analyses of All Tasks to Maximize Manipulator Dexterity (Minimize Required Approach Lengths, Required Joint Travel, Required Force and Torque at Tool Interface)
- Consider Structural Properties (Stiffness, Frequency) of Worksite
- Overall Viewing Requirements Will Drive Design (Camera Locations and Motion, Lighting, Field of View)
- Consider Placement of Work Pieces to Maximize Manipulator Dexterity
- Define the Work Piece/Tool Interface Early (Consider Safety and Loads Implications)
- Implement Human Compatibility Considerations — These Are Critical (Safety, Interfaces, Access and Clearance, etc.)
- Establish Viewing/Guiding Aids on Work Pieces and in Worksite to Aid Operator Control

Worksite Interfaces Will Determine the Ease of Operations and Training

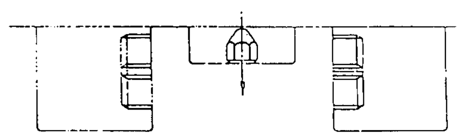
Exhibit 2-9: Considerations for Robotic Compatibility



Manipulator Preferred Work Area



Manipulator/Tool Clearance Envelopes



Gripper/Driver Interface

Work Piece Design Guidelines:

- **Single Arm Operation**
- **Combined Handle/Fastener Interface**
- **Alignment Guides**
- **Visual Cues**
- **Soft Dock**
- **Blind Mate Connectors**

Design for Robotic Compatibility Increases Utility of System and Decreases Task Times

Exhibit 2-10: Human/Machine Interface Considerations

- **Develop Human-in-the-Loop Simulations Early to Assist in Requirements Derivation and Assessment of Key Program Issues Related to Robotic Control**
- **Keep Users Firmly in the Loop through Frequent and Periodic Reviews**
- **Consider Not Only Operational Workstation in Human/Machine Design Effort, But Also Trainer, Simulator, Support Equipment, etc.**
- **Early Development of Operator Controls and Displays (Prototype Simulator) Is of Great Value in Establishing Operator Control Interface and in Estimating Procedural Timelines**
- **Workstation Mockups Are of Necessity, Even in the Age of CAD Designs**

Keep the End Users Involved to Ensure the System Will Be Used

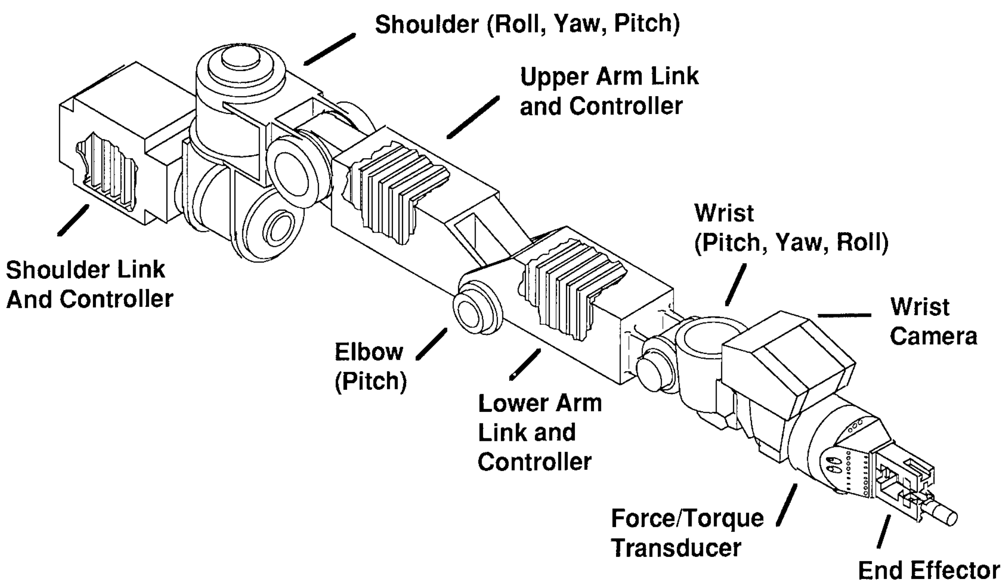
Exhibit 2-11: Data Needs Checklist

- Establish and Baseline Early in Design Data Requirements and Concepts (Operator Display, Real-time Support, Real-time Anomaly Resolution, Post-mission Evaluation)
- Include Types of Data, Bandwidth, and Accuracy by Mission Phase for Planned Operations, and for Failures/Contingency Operations
- Establish and Understand Role of Operators and Logistics Support in Nominal Operations, Trouble-shooting, and Contingency Operations
- Establish Real-time Data Needed to Be Able to Identify Failures to Correct Level
- Establish Data Required for Post-mission Evaluation, Considering Both Normal and Failure/Contingency Operations

Data Requirements Can Drive the Software and Computer Architecture

Exhibit 2-12: Robotic Manipulator

Example of a Dexterous Space Manipulator



Human Equivalency Drove the Design of This Manipulator

Exhibit 2-13: Manipulator Key Characteristics

- Two-fault Tolerant Safety Design
  - Runaway Manipulator
  - Application of Excessive Forces
  - Ability to Stow
  - Inadvertent Release
  - "Smart" Computer Failure
- Fully Embedded Electronics
- Performance and Physical Requirements Compatible with Human Task Characteristics
- Human Compatibility for Contingency Operations
- Redundant Force/Torque Sensor for End Point Force Control
- Fault-tolerant Gripper with Force and Position Control
- Control System Derived for Flight Application
  - Position and Rate Control
  - Contact Stability
  - Fully Programmable Torque Loops
  - Impedance Control
  - Inertia Decoupling

Exhibit 2-14: Sensing Alternatives

- Seeing
  - Conventional Camera Vision System with Pan, Tilt Mechanism
  - Fish-eye Vision System with Electro-optical Pan, Tilt, and Zoom
  - Capaciflector Sensor for Ranging and Imaging
  - Laser Range Finders
- Touching
  - Force/Torque Sensor at the Tool Plate
  - Tactile Sensors Imbedded in Gripper Fingers

Vision and Tactile Sensing Are the Major Senses Involved in Manipulation — Both Teleoperation and Autonomous Operation

Exhibit 2-15: Manipulator Control Definitions

- Kinematics
  - —*Forward Kinematics* : Geometrical Problem of Computing the End-Effector Position and Orientation Given a Set of Joint Angles
  - —*Inverse Kinematics* : Given the Position and Orientation of the End-Effector, Calculate All Joint Angles Which Could Result in That Position and Orientation

- Frames/Spaces
  - —*Joint Space* : Representation of Manipulator Position Relative to Joints
  - —*Cartesian Space* : Task or Operational Space Independent of Manipulator (i.e., Position of a Point Specified by X, Y, Z)
  - —*Tool Frame* : Frame Attached to the Tool Plate of the Manipulator

Robotics Control Is Constantly Concerned with the Relative Position of the Manipulator and Surrounding Objects

Exhibit 2-16: Major System-level Control Trades

Trades	Factors to Consider
Operator Interface — Teleoperation to Supervision	• Remoteness of Operation • Structure of Work Environment • Resources Available (Processing, Sensing, etc.)
Partitioning of Functions — Local/Remote	• Remoteness of Operation (Time Delays, etc.) • Safety Ramifications • Processing Capability at Both Locations
Method of Force Control — Feedback or Accommodation	• Remoteness of Operation • Processing Capability at Both Locations • Operator-in-the-Loop Involvement
Teleoperator Control Mode — Master/Slave or Cartesian Mapping	• Processing Capability at Both Locations • Space Available at Workstation
Method of Incorporating Vision — Operator Feedback or Automated Image Recognition	• Remoteness of Operation • Processing Capability at Both Locations • Work Space Structure (Lights, Visual Cues, etc.)

Several Major Trades Shape the Control System Design and They Are All Interrelated

Exhibit 2-17: Local/Remote Partitioning

An Example Based on the JPL STELER Laboratory

Local - Operator Site

- User Macro Interface to Develop Task Scenarios
- Setting of the Control Mode (Teleop, Shared Control, Supervised Autonomy)
- Remote Worksite Model Update (from Remote Sensor Data)
- Status Monitoring of the System
- Operator Coached Machine Vision
- Collision Simulator/Predictor

Two-way Communication

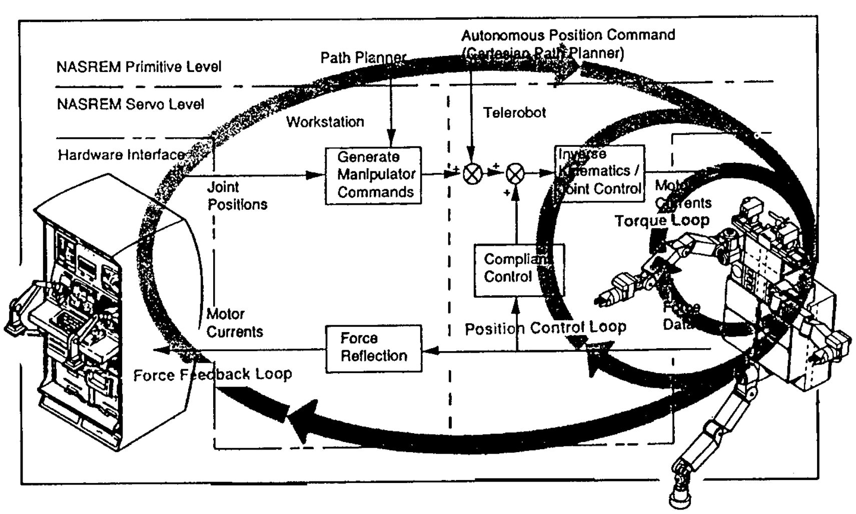
Remote - Robot Site

- System Health/Status Checks
- Position Trajectory Generation
- Sensor Data (Real or Virtual) Generation
- Force/Moment Accommodation and Compliance
- Fusion of Command As Specified by the Local Site

Proper Partitioning of Functions Makes the System Less Sensitive to Communication-related De-stabilizing Effects

Exhibit 2-18: Control Architecture

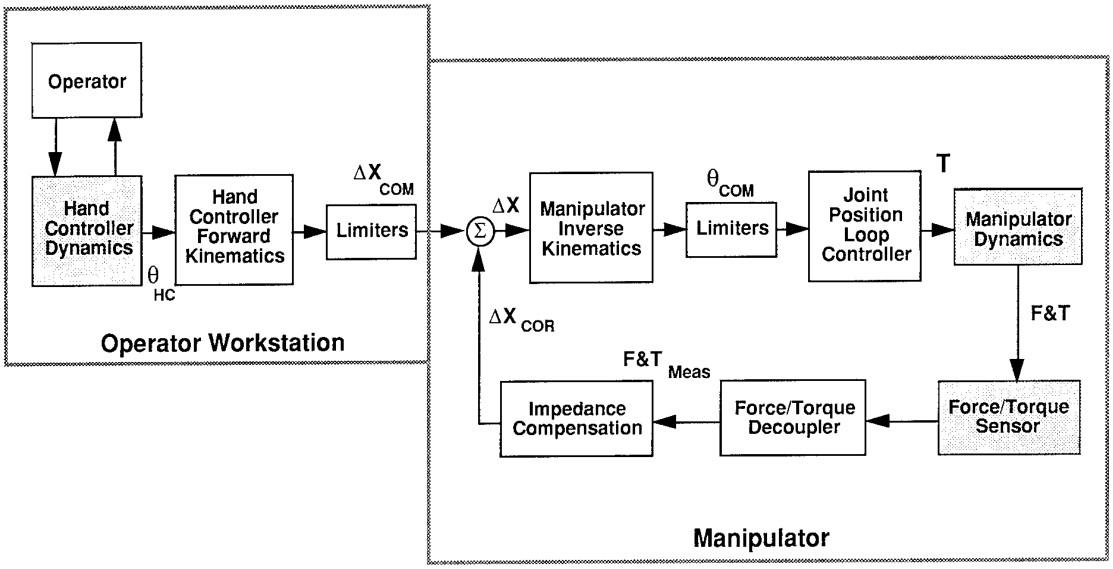
Example for a Dexterous Space Manipulator



The Control Architecture Capitalizes on the Capabilities of the Manipulator While Accommodating Limitations of the Workstation

Exhibit 2-19: Control Partitioning

Example for a Dexterous Space Manipulator



A Functional Partitioning of the Controls Is Based on the Tasks and Required Performance of the System

Exhibit 2-20: Functional Control Requirements

Example of a Dexterous Space Manipulator

Joint Space Control	Provide Single and Multiple Joint Control
Cartesian Control	Provide End-point Control
Gripper Control	Grasping Capability
Teleoperation	Ground and Local
Autonomous	Provide Joint Space and Cartesian Trajectory Capability
Gain & Degree-of-Freedom Selection	Independent Gains for Each Degree of Freedom
Control and Object Frames	Multiple Options of World, End Effector, Tool Plate and Camera Frames (Absolute and Relative)
Impedance Control	Provide Position-based Impedance Control to Modify Stiffness and Damping Characteristics for Desired Frame

The Definition of Functional Requirements Provides the Framework for Developing a Controls Architecture

Exhibit 2-21: NASREM Hierarchy

NASA/NIST Standard Reference Model for Robotic Systems

Level	Name	Function
1	Servo	Command Joint Motion
2	Primitive	Compute Dynamically Efficient Trajectories
3	E-move	Define Motion Pathways and Intermediate Poses
4	Object/Task	Decompose Actions Performed into Sequences of Motion
5	Service Task	Partition Assignments to Specific Systems
6	Service Mission	Assign Jobs and Service Resources, and Generate a Schedule of Activities

NASREM Provides a Standard for Specifying the Hierarchical Control Architecture

Exhibit 3-1: Potential Applications

Ground	Space
• General Manufacturing • Batch Manufacturing • Mining • Undersea • Construction • Health Services • Agriculture • Materials Processing • Robotics Industry • Automotive • Aerospace • Nuclear • Service Industry • Warehousing • Office/Home • Hazardous Materials Handling • Security Systems • Energy	• Robotic H/W-S/W Products — System — Manipulators — Subsystems • CCDS Applications • Servicing — Payloads — Satellite — Platforms • Materials Processing • Logistics Support • Facility Support — Laboratories — Factories — Research Platforms • Construction/Assembly • Science — Sample Acquisition — Surface Surveys

Benefits of Remotely Operated Manipulators Can Be Derived from Eliminating Humans from Hazardous Environments, Increased Productivity through Automation of Processes, and Improving Existing Processes and Techniques

Exhibit 3-2: Applications Questionnaire

Topic	Question
Understanding the Environment	• What Type of Operations, or Activities, Characterize Your Industry, or Field? • What Characterizes the Environment? • What Are the Constraints and Limitations Placed on Personnel and Machines in the Work Space?
Understanding the Task	• What Are the Characteristics of the Work Space? • What Are the Attributes of the Tasks Being Performed? • Does It Require Manipulating Objects? • Are There Safety Considerations Involved?
Understanding the Operator I/F	• If Robotics Are Currently in Use, What Is the Operator Involvement? • What Are the Operator Desires? • How Will Communications Occur with the Workstation?
Understanding the Requirements	• What Are the Characteristics of the Machine Needed? • What Are Impediments to Using Robotics? • What Are the Enablers for Using Robotics?

Judicious Selection of the Appropriate Robotic System Will Increase Benefits and Decrease Training Required

Exhibit 4-1: Human/Machine Tenets

- Machines Are More Effective Than Humans When the Task Is Routine and Can Be Completely Specified

- Humans Process Complex Data Sets Better, Work in Gestalts (Right-brain Thinking) and Deal with the Unpredictable Better Than Machines

A Synergistic Relationship Exists between Humans and Machines

Exhibit 4-2: Robotic Research Needs

- More Autonomy in Robotic Systems
- Greater Mobility and Capacity for Dexterous Manipulation
- Advances in the Human/Machine Interface

High Payoff Exists for Increased Robotic Applications by Giving Humans More Capability

CONTROL AND OPERATION OF SPACE MANIPULATOR SYSTEMS

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SUMMARY

As manned space flight passes into its fourth decade, many of the activities in space appear to be almost routine. However, the space environment is exceedingly hostile to humans and necessitates substantial effort and funding to provide an infrastructure to support human life. Increased attention is therefore being directed toward the application of robotics technology to more effectively carry out tasks in space which, up to now, have been carried out by human Extra-Vehicular Activity (EVA), or which could not be carried out because of human limitations or limitations of available equipment. Manipulator systems are better suited to operation in the external space environment and can augment or replace the human presence. They can also play an important role in the spacecraft Intra-Vehicular Activity (IVA) to replace some of the human tasks. To date few robots have been developed for space applications; however, as human activity increases in earth orbit and beyond, robotic systems will play an increasingly vital role. Control and operation of space manipulator systems are addressed with emphasis on those designed for the external space environment. Applications of the technology are discussed in the context of the Mobile Servicing System (MSS) being developed for the international Space Station. The Mobile Servicing System incorporates two manipulator systems, the Space Station Remote Manipulator System (SSRMS) and the Special Purpose Dexterous Manipulator (SPDM).

The modes of operation and selectable control features are discussed with some of the more advanced features demonstrated by simulation and laboratory test results.

1.0 INTRODUCTION

The exploration and practical utilization of space presents exceptional engineering challenges. Many of these challenges are rooted in the extremely hostile space environment. In order for humans to venture into space it is necessary to encapsulate them in a space vehicle which provides an environment similar to that on earth and shields them from the hazards of the space environment. Any Extra-Vehicular Activity (EVA) for construction, maintenance or repair outside the space vehicle requires the use of a space suit to extend that safe environment to the worksite. EVA operations require extensive preparation and training and involve many hazards with attendant high mitigating cost for simulators, under-water facilities, etc.

Robotic devices can play an important role in improving productivity and reducing the hazards of humans in space.

The International Space Station will provide a permanent base in low earth orbit for conducting space research in such areas as astronomy, materials, and life sciences. The Space Station is shown in Figure 1.

The Mobile Servicing System (MSS) being developed by Canada for the International Space Station is the first robotic system that has been assigned very diverse tasks in space, and represents the current state-of-the-art in space robotics hardware.

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Presented at an AGARD Lecture Series on 'Advanced Guidance and Control Aspects in Robotics', June 1994.

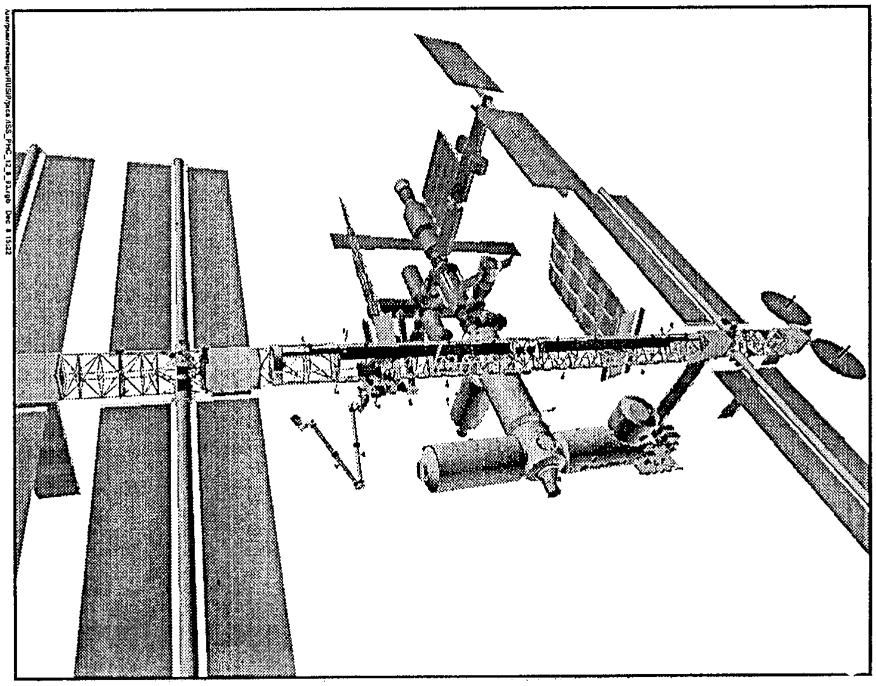

Figure 1. International Space Station

The Space Station Remote Manipulator System (SSRMS)[1], and a dual-arm robot, the Special Purpose Dexterous Manipulator (SPDM)[2] provide the robotic capabilities of the Mobile Servicing System. The two manipulator systems can work independently of each other, or they can work together with the SPDM attached to the end of the SSRMS. The SSRMS is designed to handle large payloads and the SPDM is designed to handle small payloads and perform dexterous tasks.

The control and operation of the total MSS system will be described briefly followed by separate and more detailed discussions of the SSRMS and SPDM. Emphasis is placed on the modes of operation and control and some of the built-in features designed to enhance the capability of the manipulators and reduce the workload on the human operators. Included is a brief discussion of a concept presently being developed whereby an option to operate the MSS from a ground-based control station is incorporated. This feature would further increase productivity by allowing manipulator operation by a ground-based or an in-orbit operator.

2.0 THE ROLE OF ROBOTICS IN SPACE

Manipulator systems can be designed to perform many of the tasks which are performed by humans in the external space environment. They can replace or at least augment the human activity in many areas, and can perform some tasks which humans cannot perform in space due to physical limitations. Manipulators can be designed for extended exposure to the space environment, with small operating energy consumption and very small "keep-alive" energy consumption when they are idle. The energy that is consumed is usually electrical and can be generated using on-orbit systems.

Manipulators can be designed for optimum performance of specific tasks, or a range of tasks. Large and powerful manipulators can be used to manoeuvre large payloads or assist in the assembly

of large structures. Smaller manipulators can provide more dexterous capabilities to replace electronic packages, mate/demate connectors, open/close hatches, etc., significantly reducing the requirements on the very expensive and hazardous human EVA activity. Just as earth-bound machines are designed to augment, extend or replace human capabilities, increase safety and efficiency, reduce stress, etc., intelligent space manipulators and robots can provide these features in space operations.

Few robotic devices have been developed for space applications to date. The Shuttle Remote Manipulator System (SRMS) or "CANADARM" [3] developed by Canada for the U.S. space shuttle program has been in operation for approximately 10 years. Other robotic devices have been used to obtain soil samples on Mars and on the moon. In 1993, the Robotics Technology Experiment, (ROTEX)[4] was flown during the Spacelab D-2 mission and successfully demonstrated advanced space automation and robotics technologies. The ROTEX flight system comprised a small 6 degree-of-freedom manipulator inside the Spacelab with a robot workcell with various fixtures for experimentation, and a control station with 3-D video display and 6 degree-of-freedom hand controller. The manipulator could be controlled from the Spacelab or from a control station on the ground.

Several space manipulator systems are in development: In addition to the MSS being developed by Canada for the international Space Station, the External Robotic Arm (ERA) is being developed by Europe, and two manipulator systems are being developed by Japan for use with the Japanese Experiment Module (JEM) on the international Space Station; the JEM Remote Manipulator System (JEMRMS) and the Small Fine Arm (SFA).

As the intelligence of space robotic systems increases, and as human confidence in their capabilities and safety builds, the scope of their use will no doubt increase. The autonomy of their operation will also naturally increase. Whereas present day robotic devices in space are typically commanded at a fairly primitive level, i.e., "move in direction x", or "perform automatic sequence of motions a-b-c". in the future, more intelligent devices with sophisticated sensing systems might respond to "replace electronic package 'a' on device 'xyz'". The planning of the detailed operations and the problems of dealing with non-routine occurrences during operation will tend to shift away from the human planners and operators to the robotic systems as the intelligence of the robotic devices increases.

The design and operating features of the Mobile Servicing System will now be discussed.

3.0 MOBILE SERVICING SYSTEM

The Mobile Servicing System is Canada's contribution to the international Space Station and will play a predominant role in the assembly and maintenance of the Space Station. The MSS is being developed by Spar Aerospace Limited for the Canadian Space Agency. It is designed to be repaired and maintained in orbit and will have the capability to handle payloads with mass properties up to and including those of a fully loaded shuttle orbiter. The MSS will also incorporate the capability to relocate its manipulator systems on the space station.

During assembly and operation of the Space Station, many operations in the external environment will be required. These operations will be carried out by means of Extra-Vehicular Activity of the Station crew and by manipulator systems.

The MSS is being developed to satisfy the following functions for the Space Station:

- Space Station Assembly
- Space Station external maintenance
- transportation on the Space Station
- servicing of external payloads
- deployment and retrieval functions
- EVA support

The MSS comprises a space segment and a ground segment. In order to carry out this diverse set of functions, the space segment design consists of four elements:

- the Mobile Servicing Centre (MSC),
- a Special Purpose Dexterous Manipulator (SPDM),
- a MSC Maintenance Depot (MMD),
- a dedicated control station.

The ground segment is made up of facilities to provide engineering support to operation, training, task verification and sustaining engineering functions. The MSS Architecture is shown in Figure 2.

The MSC, depicted in Figure 3 with the SPDM attached, comprises the Space Station Remote Manipulator System, an operations platform called the MSC Base System (MBS), and a United States supplied Mobile Transporter (MT). The MT is designed to move along rails on the Space Station truss to transport the MBS, SSRMS, SPDM and other payloads. The capture, manipulation and berthing of large payloads is performed by the MSC using the SSRMS.

MSS functions requiring dexterous capabilities are satisfied by the dual-arm SPDM. The SPDM will play a role in the Space Station maintenance, assembly, and in payload servicing. It is capable of operating from fixtures on the MBS, from the end of the SSRMS, or from appropriate fixtures on other structure.

Because it is permanently installed on the Space Station, repair and maintenance of the MSS must be performed on orbit. The MBS is designed to provide appropriate positioning of the SSRMS and SPDM for maintenance. The MMD is configured to store a complement of critical MSS replacement components and tools.

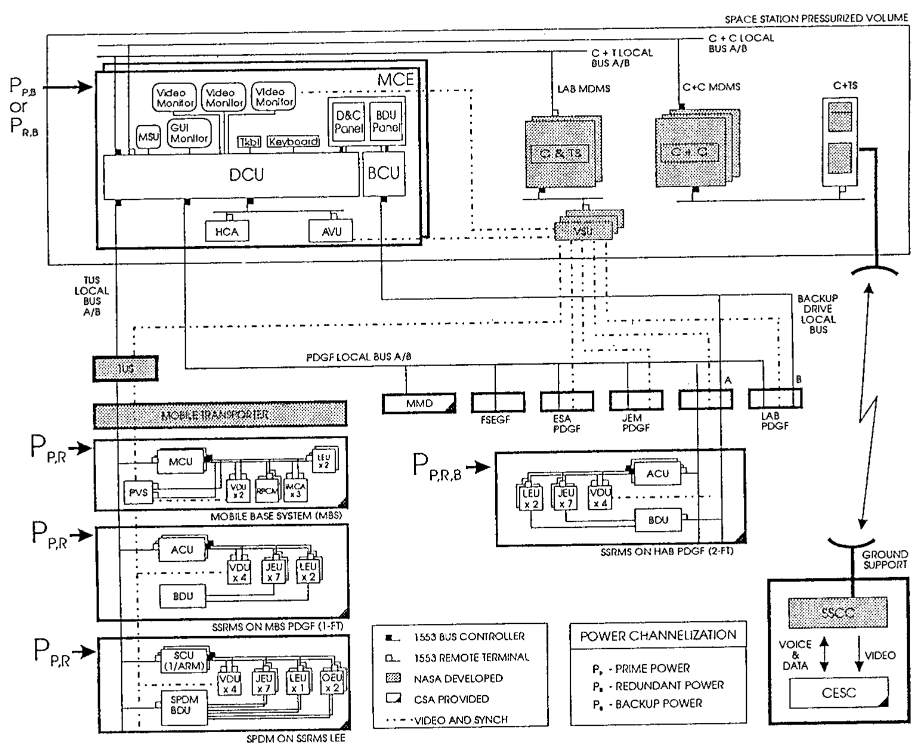

Figure 2. Mobile Servicing System Architecture

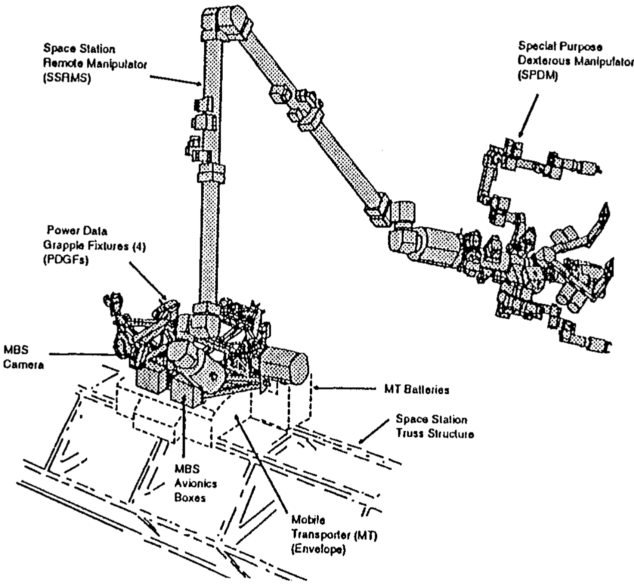

Figure 3. Mobile Servicing Centre with SPDM

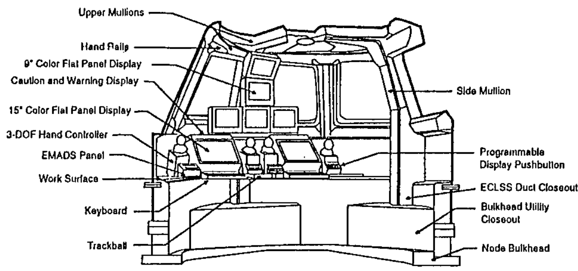

Figure 4. MSS Control Station

A dedicated control station is used by the MSS operator to command and monitor MSC and SPDM operations from a pressurized, shirt-sleeve environment on the station. The control station is shown in Figure 4. The control station-to-operator interface includes a number of displays for video views of operations, a command and control display providing graphical and numerical information and soft keys which are activated by a trackball input, two hand controllers for inputting manual manipulator commands, and a keyboard.

Concepts are presently being developed for an additional control station to be included in the MSS Ground Segment. This control station would have a similar operator interface but would include some additional features to accommodate communications delays and other problems associated with remote operation. This control station would provide the optional capability to operate the MSS from the ground.

4.0 SPACE STATION REMOTE MANIPULATOR SYSTEM

The SSRMS, as shown in Figure 5, is a 7-joint symmetrical manipulator approximately 17 metres in length when fully extended. A symmetrical arrangement of joints and a Latching End-Effector (LEE) at each end allows either end to attach to payloads, or to serve as a base for the SSRMS providing that an appropriate Power Data Grapple Fixture (PDGF) interface is available. The LEE along with the PDGF interface are shown in Figure 6. The LEE incorporates a snare mechanism, a rigidizing carriage mechanism, a latching system and umbilical connection. The snare mechanism is designed to snare the protruding probe of the grapple fixture. After the snare is closed, the carriage containing the snare mechanism and the snared probe is drawn into the LEE until the grapple fixture base plate is in full contact with the face of the LEE with a specified preload. If a higher stiffness interface is required, or if the power and data is to be transferred across the interface, a latching mechanism is activated, and an umbilical connector is engaged with its mating connector on the Grapple fixture. Power, data and video may be passed through the SSRMS to operate the SPDM while attached to the SSRMS LEE or to support the keep-alive power, telemetry and command requirements of payloads attached to the LEE. Four video cameras are mounted on the SSRMS, one fixed camera at each end effector, and one, along with a pan and tilt unit on either side of the elbow joint on the main booms. A light is provided with each of the cameras.

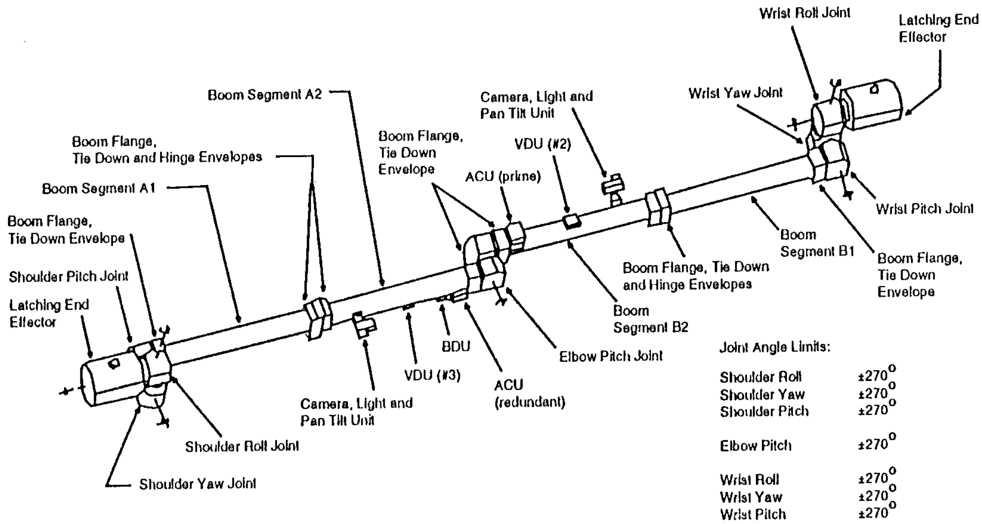

Figure 5. Space Station Remote Manipulator system

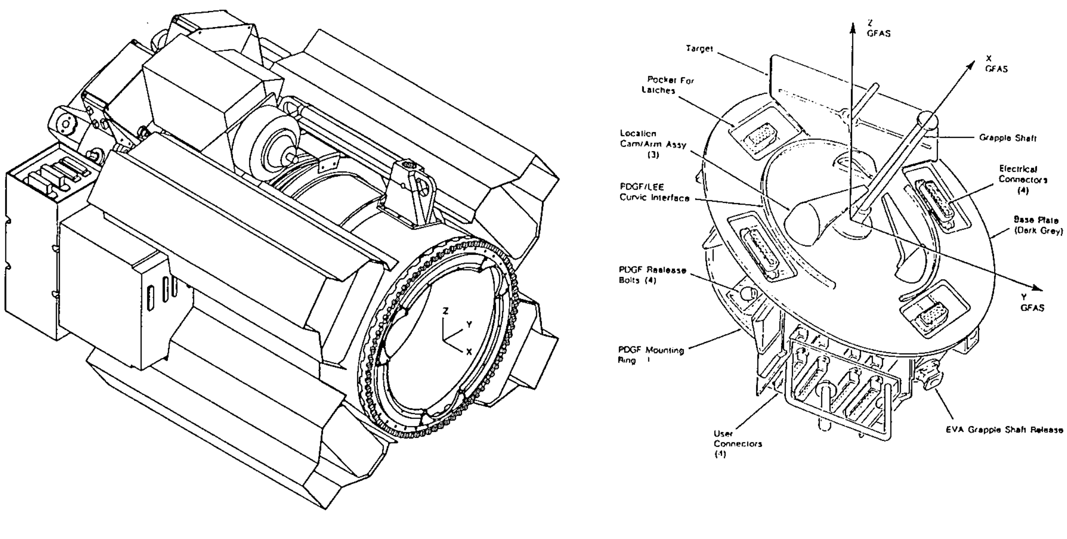

Figure 6. Latching End Effector and Power Data Grapple Fixture

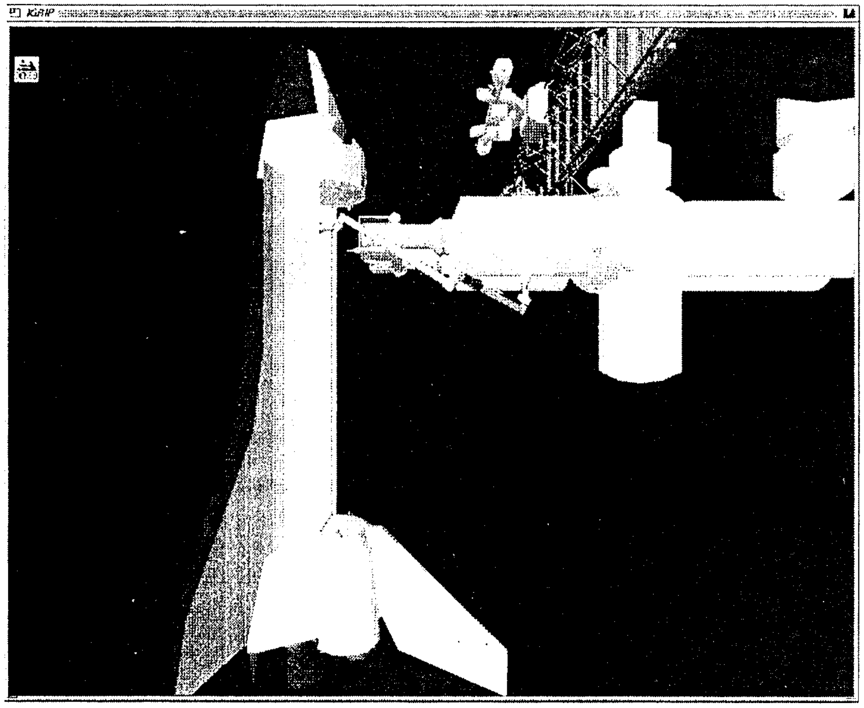

Figure 7. Shuttle Berthing Operation using SSRMS

Although the majority of SSRMS operations will be performed from the Mobile Base System, the symmetrical arrangement of joints and LEEs gives the SSRMS a self-relocating capability. PDGFs mounted strategically along the Space Station allow the SSRMS to step from one PDGF to another to access areas which cannot be reached when operating from the MBS.

The 7 joints of the SSRMS are arranged in clusters of three joints near each end of the manipulator to act as a "wrist" and "shoulder" respectively, with an additional joint at the midpoint "elbow" position. Starting from either end, the joint sequence is roll, yaw, pitch, pitch, pitch, yaw, roll. All joints are identical and have a range of travel of +/-270 degrees. Because the number of joints exceeds the 6 degrees-of-freedom in which the manipulator tip is being controlled, the manipulator is classified as kinematically redundant. The kinematic redundancy increases the operational flexibility helping to avoid kinematically singular configurations.

4.1 Major SSRMS Performance Requirements

Operations using the SSRMS involve the handling and positioning of a wide range of payload shapes and mass properties. The mass range of payloads which can be handled by the SSRMS is from zero (i.e., no payload) up to 116,000 Kg, which is representative of a fully loaded shuttle orbiter.
A computer generated view of the SSRMS performing a manoeuvre to berth the shuttle orbiter to the Space Station is shown in Figure 7.

The ability to stop the SSRMS and its attached payload within a known distance when the manipulator is commanded to stop, or when an emergency stop is initiated, is of crucial importance to avoiding damage to the SSRMS or other equipment. The stopping distance/angle requirements of the manipulator tip and payload set the maximum manoeuvring rate requirements for various payload sizes and influence the sizing of joint actuators, drivetrains, emergency braking devices, etc. By manoeuvring within the maximum rate, stopping can always be guaranteed within the

specified distance (usually 0.3 m) even in the event of failures.

Large payloads must be manoeuvred at very low rates to satisfy stopping requirements. In order to ensure good controllability at these low rates, the control system must exhibit high rate accuracy (low drift). SSRMS drift rate is specified to be better than 3 mm/sec.

Assembly and berthing operations require accurate positioning of payloads to accommodate the capture range of mating devices and berthing mechanisms. The open-loop accuracy of the SSRMS (based on joint angle measurements) is specified as 4.5 cm/ 0.7 deg. The resolution of motion capability is specified to be better than 1 cm and 0.1 deg. Significant improvement on the open-loop positioning is therefore possible if good visual cues are available in manual modes, or if vision system feedback is used in automatic modes.

Constrained motion operations during assembly operations or payload berthing require that interface loads are limited to prevent jamming or damage to equipment. Static loads at the SSRMS tip are specified not exceed 1000 N and 3100 N-m during constrained motion operations. There is also a requirement for the SSRMS to be capable of actively limiting static loads at the tip by means of force-moment accommodation, to selectable values in the range of 0 to 445 N/407 N-m.

5.0 SPECIAL PURPOSE DEXTEROUS MANIPULATOR

The SPDM is shown in Figure 8. The robot is made up of two major assemblies; a base segment and two manipulator arms. The base segment has a latching end effector at one end, which is the same as the SSRMS LEE, and a PDGF at the other end which is compatible with the SSRMS LEE. Thus the SPDM can be attached to the SSRMS to act as an extension to the SSRMS, or it may be attached to a PDGF on the MBS or at other locations on the Space Station. A shoulder structure supporting the two arms is attached to the base on the PDGF side of a body joint. This allows the upper body, including the arms to rotate relative to the LEE. A platform is attached to the LEE side of the base with accommodation for the storage of tools and transport of ORUs.

The two SPDM arms are identical 7-joint manipulators with a clusters of 3 joints at the shoulder and near the tip, with a pitch joint at the elbow position near the midpoint of each arm. The arms have the same joint sequence as the SSRMS and are therefore described by similar kinematic equations. The tip of each arm is equipped with an ORU-Tool Changeout Mechanism (OTCM) and the wrist of each arm contains a six axis force-moment sensor. The OTCM is depicted in Figure 9. It incorporates a parallel jaw gripper compatible with standard H and micro fixtures, an extendable 7/16 inch socket drive, a camera with a two stop zoom lens, two lights, and an extendable umbilical mechanism. In addition to the OTCM cameras, there are cameras with pan and tilt units on the fore part of each arm and on each side of the body. There is also one fixed camera on the SPDM base LEE, for a total of 7 cameras. Each camera is collocated with a light.

An interface is provided on the SPDM to attach an ORU carrier with the capability of transporting up to six ORUs, allowing several ORUs to be replaced during a single mission.

5.1 Major SPDM Performance Requirements

The SPDM is employed for numerous dexterous operations involved with assembly and maintenance such as handling and replacing ORUs, connecting/disconnecting utilities, attaching covers, opening hinged doors, and performing operations with special tools. Operations are performed while the SPDM is mounted through its PDGF interface on the end of the SSRMS, or through its LEE interface on the MBS or on the Space Station. While operating from the SSRMS, the OTCM of one of the SPDM manipulators is usually attached to a standard H interface on structure near the worksite to stabilize the SPDM while the other arm performs the dextrous task. Some operations

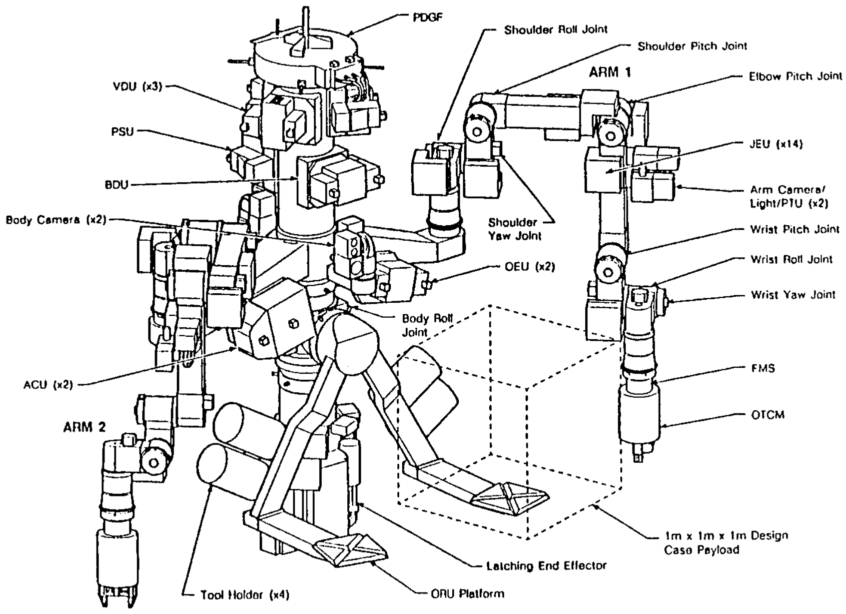

Figure 8. Special Purpose Dexterous Manipulator

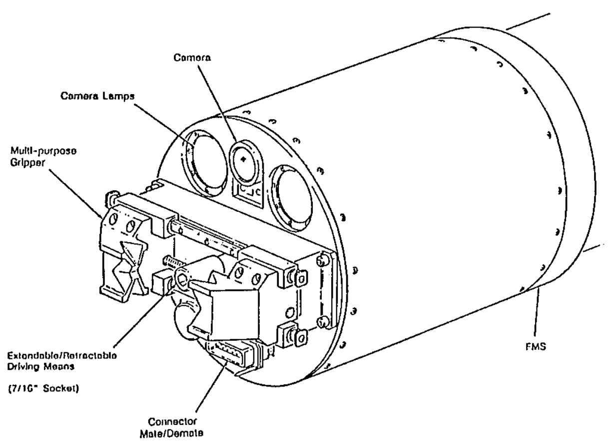

Figure 9. ORU/Tool Changeout Mechanism

require the use of both arms without the added stabilization. Some of the performance specifications must therefore take into account the significant variation in support stiffness for these operating configurations.

Figure 10 is a computer generated graphics view showing the SPDM preparing to remove a battery box from a carrier. Note that the SPDM base PDGF is attached to the SSRMS LEE and that the OTCM of one of the SPDM arms is attached to a grasp interface on a nearby beam for added stability.

The range of design case payloads which may be handled by the SPDM is from zero (no payload) to 600 Kg. with maximum dimensions of 1 metre square.

As with the SSRMS, the stopping distance requirements and maximum interface loads requirements determine the maximum translational and rotational manoeuvring rates and influence the design of actuators, drivetrain and emergency braking systems. Maximum stopping distance/angle during payload manoeuvring operations are specified as 5 cm/1.75 deg. During ORU removal and insertion, there is also a requirement on the maximum impact energy at the interface, which also determine the maximum rates for this class of operation.

During constrained motion operations such as

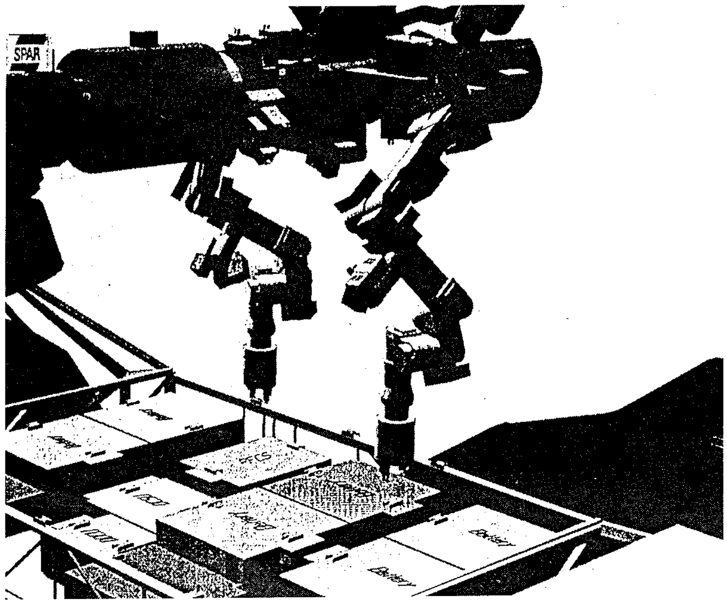

Figure 10. SPDM Performing Battery Box Changeout

insertion of an ORU into guides, the positioning accuracy and the accuracy of motion is of utmost importance. The open-loop positioning accuracy of the SPDM manipulators is specified to be better than 6 mm and 1 degree. Specification of smaller minimum positioning increment and specifications on the resolution of visual cues and on the AVF allow improvement over the open-loop accuracy by operator adjustments in manual modes, or through the use of AVF supported automatic modes. The accuracy of motion or minimum tip velocity the manipulators is specified to be 2 mm/sec and 0.06 deg/sec.

In order to accomplish ORU insertion or removal, the SPDM manipulators are required to be capable of applying insertion and removal forces in the range of 22 to 111 N for up to 30 seconds.

Maximum interface loads between the OTCM and payload are specified as 222 N and 169.5 N-m to avoid damage to equipment. There is also a requirement on the force-moment accommodation feature to actively limit the forces and moments to selectable values within that specified range.

6.0 VISION SYSTEM

A major operational component of the MSS control equipment is the Artificial Vision Unit (AVU) which will play an important role in the manual and automatic operation of both the manipulators and cameras. In one mode the AVU will provide data to the MSS operator in the form of graphical and textual displays. In another mode the AVU will provide outputs which can be used in real-time to implement automated tracking modes in the MSS manipulators. The AVU is capable of utilizing the output of any of the MSS or Space Station cameras.

In October 1992, on Shuttle mission STS-52, a machine vision system, called the Space Vision System (SVS), flew in space for the first time[5]. The flight tests verified the fundamental principles of using real-time photogrammetry techniques on a flexible space-based platform such as a shuttle or space station. The photogrammetry techniques used are the core of the AVU. A series of experiments were conducted covering many of the baseline requirements of the AVU, as well as many of the features related to manipulator tasks.

It was shown, using SVS displays and the SRMS, that an operator could control the manipulator with substantially more precision than is possible without the displays.

7.0 MSS MANIPULATORS CONTROL SYSTEM DESIGN AND OPERATION

It is evident from the above descriptions of the SSRMS and the SPDM manipulators that the manipulators are of a similar kinematic configuration and that their tasks and performance requirements are similar in many ways, although on a different scale. This comes about because of the general purpose nature of both systems, although they are intended to operate in different payload ranges and with different degrees of dexterity. Indeed, the design of the control systems for the SSRMS and for the SPDM manipulators are, in principle, almost identical. In most cases, only parameter values for the system and control laws differ. The description of the control system design will therefore be discussed with respect to both the SSRMS and SPDM. Differences will be pointed out.

The MSS manipulators are controlled from a control station in the pressurized Space Station environment (Figure 4). A requirement to include the capability to control the MSS from a ground-based command source through a radio link has recently been baselined. The concept which is presently being studied is discussed in Reference 6 and is depicted in Figure 11. The ground control station human interface would be similar to that on-orbit, but with special features to deal with problems unique to controlling from a distant source, namely communications delays of several seconds, and reliance on a software-based world model for the manipulator operations. The concept includes the possibility of using predictive simulation with animation and graphics to provide the operator with a non-delayed representation of the manipulator response. Concepts are also being developed to update the world model in real-time in order to better predict the exact location of objects in the manipulator workspace. This information is critical when performing contact, or close proximity operations.

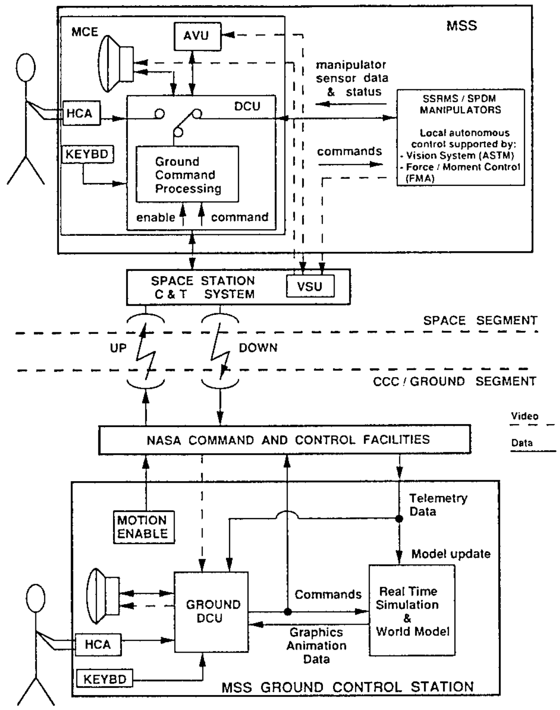

Figure 11.
MSS Ground Control Functional System Concept

A block diagram of the SPDM control architecture for the on-orbit control concept is shown in Figure 12. Additional detail of the MSS architecture may be found in Reference [7]. The control architecture for the SSRMS is similar to that in Figure 12 but would not contain blocks for the second arm, body joint or SPDM LEE. References to the OTCM would be replaced by LEE, and OEU by LEU for the SSRMS. This control concept allows the MSS manipulators to be operated in a number of human-in-the-loop and automatic modes.

7.1 Operating Control Modes and Features

The control modes and features described here for the MSS manipulators reflect the state-of-the-art for the current generation of external space robotics. Because of the unique problems

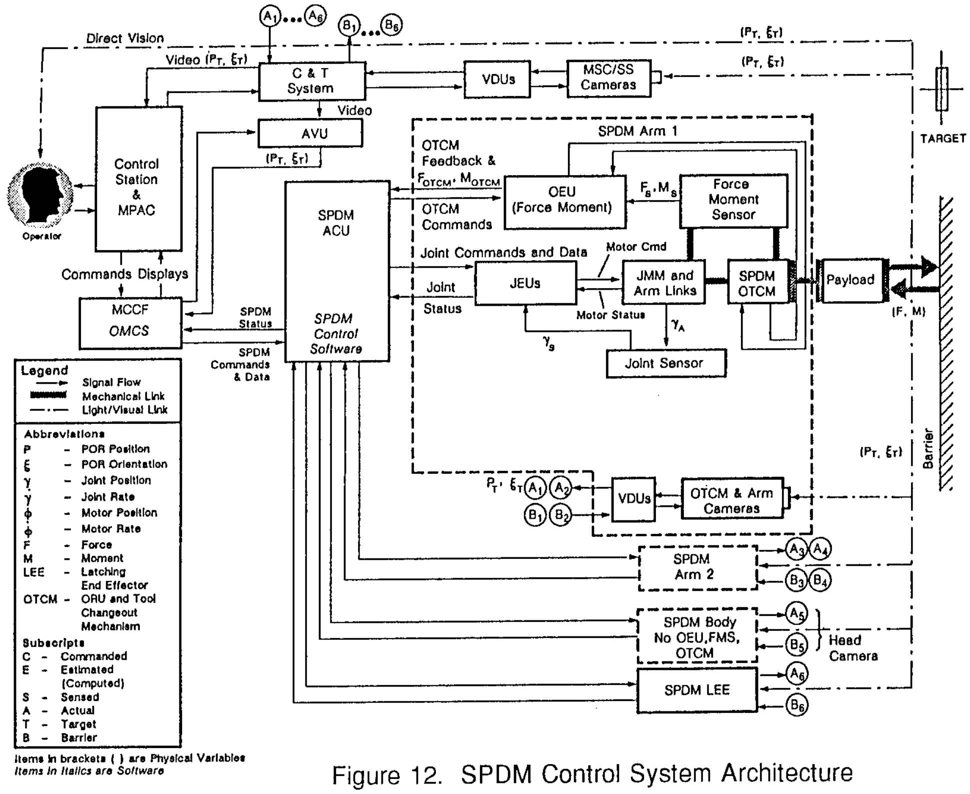

Figure 12. SPDM Control System Architecture

encountered in the space environment, it is believed that many of the characteristics of the MSS manipulator modes and features would be typical of the modes and features of most general purpose manipulators designed to perform a wide variety of tasks in space. Simpler, special purpose manipulators would not incorporate all of these features, or may require other special features to suit their specific purpose.

Control Modes

The control modes for the SSRMS and SPDM manipulators are described briefly in Table 1.

TABLE 1. MSS MANIPULATOR CONTROL MODES

CONTROL MODE	COMMANDED MOTION
HUMAN IN THE LOOP CONTROL MODES	
Manual Augmented	Manipulator receives hand controller data and moves selected POR at the specified rate.
Single Joint Rate	Movement on joint-by-joint basis. Other joints in Joint Position Hold.
Back-up Drive	Movement on joint-by-joint basis using BDU. Brakes on for all other joints.
AUTOMATIC TRAJECTORY	
Operator Commanded POR	Control of POR from its current position to operator-specified destination.
Operator Commanded Joint Position	Control of joints from current positions to operator-specified destinations.
Prestored POR Auto Sequence	POR commanded along predefined trajectory.
Prestored Joint Position Auto Sequence	Joints move in a predefined joint position sequence.
AVF Supported Tracking	Manipulator responds to relative position information generated by AVF and provided by MCCF.

Motion commands to the manipulators can be resolved motion commands or joint-by-joint commands. In resolved motion operation, translational and rotational velocity inputs from an operator or automation software provide commands in a selected Point-of-Resolution (POR) reference frame. The origin of the POR frame is typically chosen to be the arm tip or a point of interest on a payload or tool. Inverse kinematic equations in the arm control software resolve the POR commands into individual joint commands to the joint servos. For joint-by-joint operation, commands in the individual joint axes are input directly to the joints.

Because of the kinematic redundancy of the 7-joint manipulators, the inverse kinematics equations in the control laws have a multiplicity of solutions. The result is uncertainty in the arm configuration for a specific tip position and orientation. This problem is handled in the control laws by providing an option to apply an additional constraint to control one of the joints (usually a shoulder joint) to a constant position unless it is required to move to avoid a kinematic singularity.

Although resolved motion operation is the primary means of controlling the manipulators, joint-by-joint operation is an option in both human-in-the-loop and automatic modes.

Manual Augmented Mode - In the Manual Augmented mode, the operator provides translational and rotational velocity inputs by means of two 3 degree-of-freedom hand controllers to command a selected POR. Feedback displays to the operator at the control station include POR position and orientation and associated rates, joint positions and rates, camera views, and representation of tip forces and moments. As will be discussed later, the force-moment signals may be used in a closed loop to provide force-moment accommodation as an inner loop to the operator control loop.

Single Joint Rate Mode may be used by an operator to position one joint at a time. The operator provides a joint rate input command to a selected joint. Other joints are held at a fixed position by the joint servos.

Backup Drive mode allows joint-by-joint motion using a separate Back-up Drive Unit (BDU). This mode is used to bring the manipulator to a safe state after the unlikely occurrence of multiple failures has disabled primary and redundant channels of operation.

Automatic POR Modes - In the automatic POR modes, the POR is commanded to move from an initial position to a destination position in space along a straight-line trajectory. The destination position may be specified by the operator (**Operator Commanded POR mode**), or a series of such manoeuvres can be chained together and called up to form an automatic sequence of moves (**Prestored POR Autosequence mode**). Alternatively, the Artificial Vision Function (AVF) can provide real-time target data for tracking of a stationary or moving visual target.

AVF Supported Tracking mode - The AVF provides a significant advance in the automation of space manipulators and cameras relative to the Shuttle manipulator. Figure 13 is a block diagram of the AVF Supported Tracking mode.
A key element of the AVF is the Artificial Vision Unit (AVU) which processes the images from MSS or Space Station mounted cameras in real time and outputs positions orientations and velocities of target patterns with respect to the camera, or with respect to a reference target in the field-of-view. The outputs can be displayed to the operator, used to track targets with cameras with pan and tilt capability, or to provide feedback to control the SSRMS or SPDM manipulators in an AVF Supported Tracking mode. While tracking a target in this mode, operator inputs from hand controllers, or stored data can be used to change the camera-to-target tracking distance setpoint in real time. This feature is useful in operations such as automatic berthing.

The feasibility of automated tracking of targets and berthing of payloads using the AVF has been demonstrated by simulation for the full range of SSRMS payloads including the 116,000 Kg payload representative of a loaded Shuttle orbiter. A simulation response is shown in Figure 14 where a 22,900 Kg payload, representative of a Habitation module, is manoeuvred from offset initial conditions to a position and orientation within the capture range of the berthing mechanism (7.6 cm / 1.5 deg). For the simulation it is assumed that the berthing mechanism is equipped with a boresight camera, and that the AVF target on the payload is in its field-of-view and lock-on has been achieved. Initial offsets in translation are approximately 0.8 metre in x, along the camera boresight and about 0.2 metres normal to the boresight. Angular offsets of the target axes with

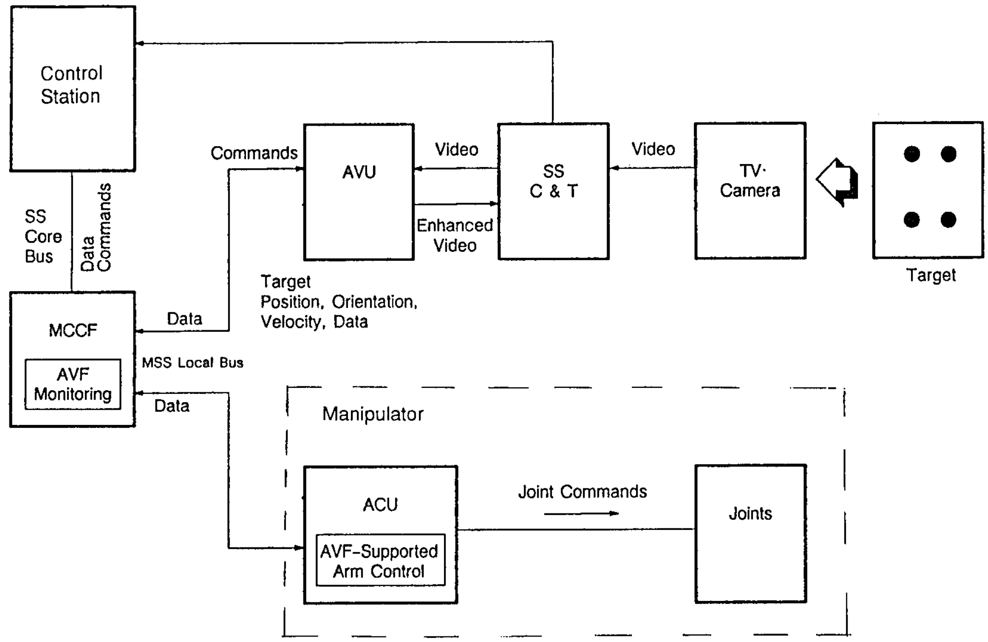

Figure 13. Artificial Vision Function Block Diagram

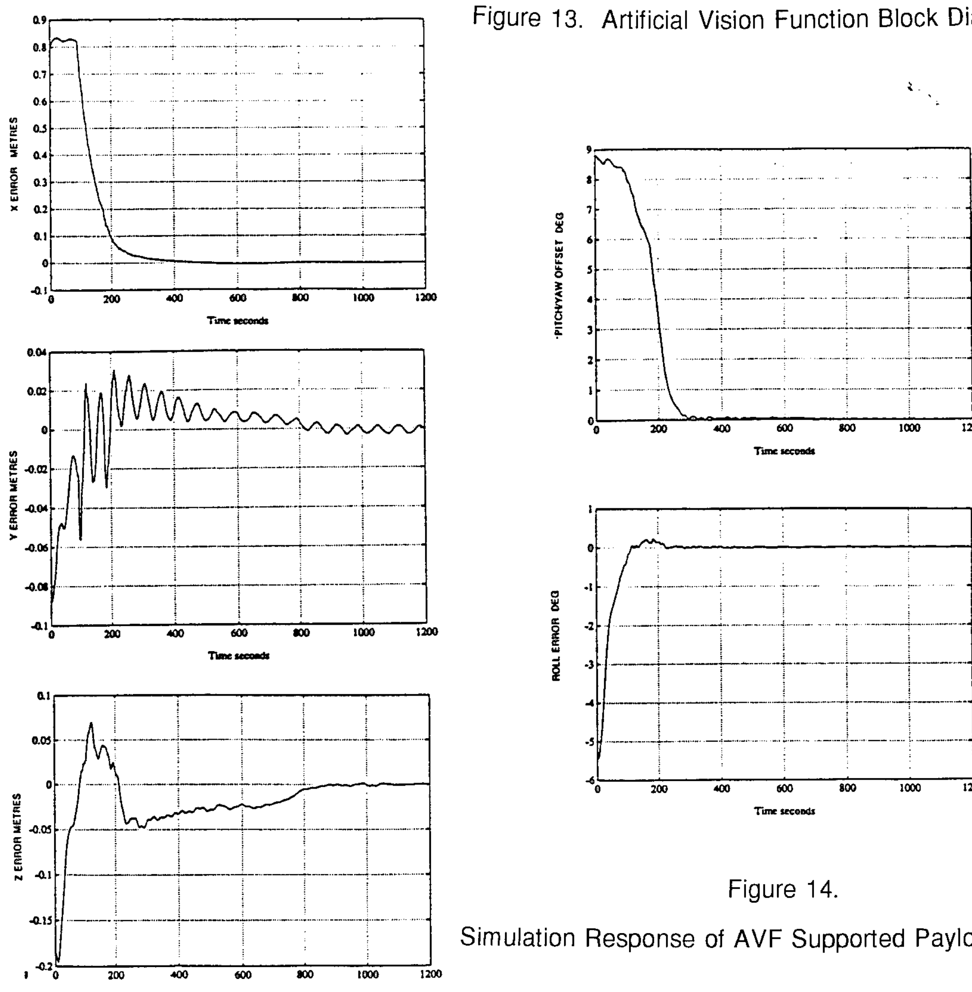

Figure 14.

Simulation Response of AVF Supported Payload Berthing

respect to the boresight is approximately 9 degrees, with a roll offset of 5.5 degrees. Prior to the automatic berthing operation, the module is assumed to have been manoeuvred to the vicinity of the berthing mechanism with these offset initial conditions. Perfect alignment is achieved when all of the offsets have been nulled. The SSRMS is modelled as a chain of flexible bodies and includes the dynamics of the servomechanisms and drivetrains in the joints. The payload is modelled as a rigid body, and the AVU and camera are modelled as an ideal sensor with a processing delay.

The simulation response shows that the translational and rotational displacements converge smoothly to within the capture range in approximately 250 seconds and converge to very small values shortly thereafter. The time required to achieve the berthing mechanism capture conditions is comparable with timelines for manual berthing.

Joint Automatic modes - The joint automatic modes are analogous to the POR auto modes. In the **Operator Commanded Joint Position mode**, the operator specifies a destination set of joint positions. The joints are commanded to move from their current positions to the destination positions. In the **Prestored Joint Position Auto Sequence mode** a series of such joint manoeuvres can be chained together and called up to form an automatic sequence of joint moves. The joint automatic modes are particularly useful in setting up specific arm poses in preparation for other operations, or to deploy an arm from a stowed position.

Control Features

A number of control features may be selected by the MSS operator to enhance manipulator capabilities and reduce the operator workload. The features are made selectable because they are often useful only for a specific type of operation, or a specific manoeuvre within an operation. A list of the selectable features and a brief description of each is given in Table 2. The function of some of

TABLE 2. MSS CONTROL FEATURES

FEATURE	DESCRIPTION
Force-Moment Accommodation (FMA)	Provides backdriving in response to measured external forces and moments.
Line Tracking	In POR Auto Modes, controls POR position and orientation to the commanded "straight-line" trajectories.
Rate Hold Selection	Holds rates commanded at the time of selection, in Manual modes.
Rate Limit Selection	Allows selection of rate limits within the maximum for a particular payload.
Position/Orientation Hold Selection (POHS)	Controls uncommanded degrees-of-freedom in Manual Augmented Mode.
Rate Input Scale Selection	Allows selection of rate command scale between vernier and course rates.
Coordinate Re-referencing	Allows selection from a variety of command and display coordinate systems.
Manual Mode Trajectory Processing	Allows storage of manual mode commands for later off-line processing.
Self Collision Avoidance	Algorithm which prevents collisions between MSS elements.
Trajectory Pause/Resume	Allows a pause and resumption of motion in Automatic modes.
Arm Pitch Plane Change (APPC)	Commands arm plane rotation while keeping the POR stationary.

the features is simple and clear from the brief description in the table. Some of the more advanced and complex features warrant additional discussion.

Force-Moment Accommodation (FMA) - During constrained motion operations where the manipulator or its payload come into contact with other structure, some means of limiting forces and moments at the contact interface is necessary to prevent jamming and possible damage. Force-moment accommodation provides an active compliance characteristic which acts to relieve the contact forces and moments.

A simplified block diagram describing the force-moment accommodation control loop is shown in Figure 15. The complex, 6 degree-of-freedom contact dynamics is represented symbolically by a simple single degree-of-freedom "barrier". The combined stiffness of the manipulator and "barrier" acts as a gain factor in the feedback loop and can therefore give rise to dynamic stability problems.

When FMA is selected, the manipulator is commanded in the normal way in Manual or automatic POR modes. However, signals representing the 3 force and 3 moment components derived from the force-moment sensor near the tip

of the arm are fed back to modify the POR rate commands. This provides an active compliance in the directions of the applied forces and moments. Nonlinear processing in the feedback loop allows the setting of force-moment limits in real-time from the operator control console. Because of the dynamic stability problems referred to above, the FMA control loop necessarily has a relatively low bandwidth and is therefore not effective in controlling impact loads.

Figure 16 shows the results of a laboratory test demonstrating the effectiveness of FMA. In the test, the experimental robot gasps a fixed interface with an initial 1.3 cm lateral misalignment. The end effector forces and moments required to align the end effector to the fixed interface are shown for the case without FMA and then with FMA. The action of the FMA in relieving contact forces is clearly evident. The effect of the low bandwidth of the FMA controller is demonstrated by a spike in the response during a rapid change in load (impact).

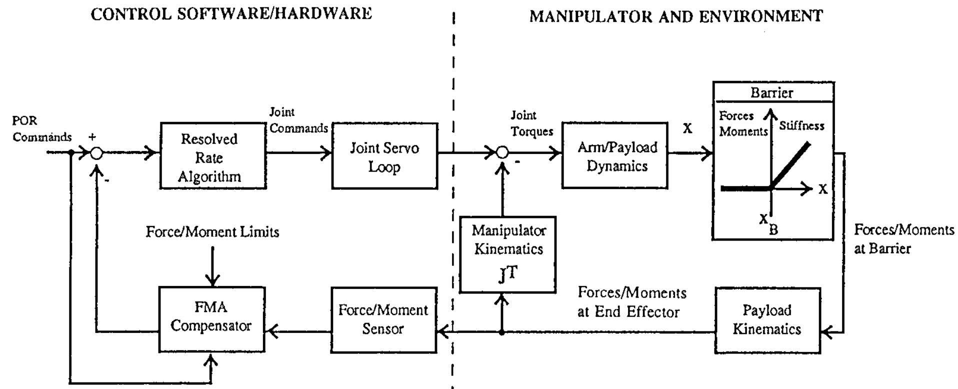

Figure 15. Force-Moment Acommodation Simplified Control Loop

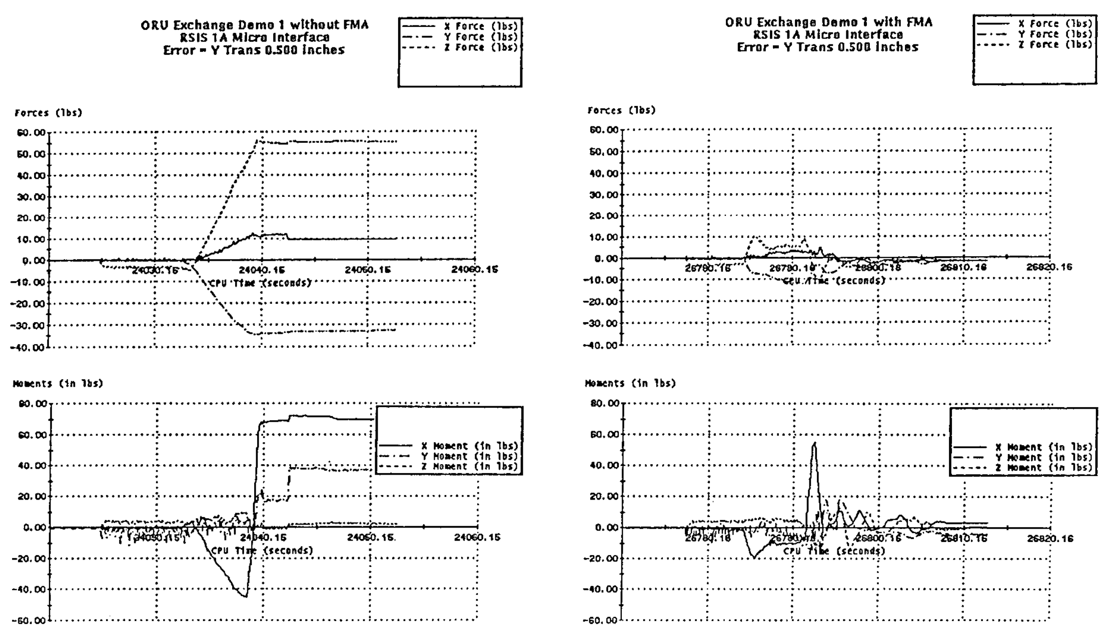

Figure 16. Force-Moment Accommodation Laboratory Test Response

Line Tracking may be selected in POR auto modes to control the deviations of the POR from commanded "straight line" trajectories in translation and orientation. During an automatic manoeuvre, dynamic transients and disturbances can cause the response of the POR to deviate from the commanded trajectory. If Line Tracking is *not* selected, these deviations from the original commanded trajectory are not corrected. Instead, at each control commutation cycle, the POR is commanded to continue along a new straight line from its present off-track position toward the destination. While the destination may still be achieved, some operations require manoeuvres down narrow corridors to the destination to avoid collisions. With Line Tracking selected, deviations from the original trajectory are calculated and fed back to control the POR to the original trajectory.

Position/Orientation Hold Selection (POHS) - POHS may be selected in Manual Augmented mode to automatically correct deviations due to disturbances in uncommanded POR degrees-of-freedom, thus relieving the operator from manually correcting these errors while performing a manoeuvre. One of two options may be selected: "Hot-stick" or "Manual" POHS. When "hot-stick" is selected, the operator inputs hand controller POR rate commands in the normal way. However, at each control computation cycle, translational and rotational vectors are generated from the hand controller signal which act as reference trajectories. Translational and rotational deviations in response normal to the vectors are automatically corrected. The result is that motion in uncommanded directions is automatically corrected, leaving the operator to concentrate on motion in the commanded degrees-of-freedom. "Manual" POHS is similar except that rate command signals from selected hand controller degrees-of-freedom are set to zero. This option is useful when a manoeuvre is carried out along a specific hand controller axis or set of axes. Uncommanded axes are blocked out to avoid inadvertent command inputs.

Self Collision Avoidance - The SSRMS and SPDM differ in the area of collision avoidance. The SSRMS uses joint angle measurements to stop motion when a self collision or collision with the MBS or its equipment is imminent. The SPDM provides automated collision avoidance between each of its manipulators, its body and attached payload. Where possible, the collision avoidance feature uses the kinematic redundancy of the active arm to avoid collisions without affecting the tip trajectory. If the collision cannot be avoided in this way, the trajectory is modified to avoid the collision.

Arm Pitch Plane Change (APPC) - It is sometimes necessary or convenient to rotate the arm pitch plane independent of payload motion to avoid collisions, to allow better viewing, or to avoid joint limits. The arm pitch plane is the plane defined by the origins of the three consecutive pitch joint reference frames of the SSRMS or SPDM arms. The APPC feature allows the operator to use a hand controller input to rotate the arm pitch plane about the line joining the origins of the shoulder pitch and wrist pitch reference frames. The kinematic redundancy of the SSRMS and SPDM manipulators allows this pitch plane motion while the tip of the manipulator is held stationary.

8.0 SIMULATIONS

Simulations are a critical tool for the development and operation of space robotic systems. Due to the design of space manipulators for operation in a weightless environment and the attendant very high ratio of payload capacity to manipulator mass, the construction of hardware models which are fully functional in a 1-g environment is very difficult or impossible, as in the case of the SSRMS.

High-fidelity real-time and non-real-time simulations are required in the development phase for feasibility studies, requirements development, the design of manipulator control systems, control modes and the human-machine interface, and the verification of the overall human-machine system design as well as the manipulator handling performance before flight. For space robotic operations, simulations are used for operations

planning and support, operator training and sustaining engineering.

In the development of simulations for the MSS particular challenges arise due to the need to simulate high-order dynamic systems with multiple elastic bodies which can be connected in different topologies such as chains, trees, loops and nests. The need to simulate the transition from one topology to another, e.g. during an ORU change-out operation, and to represent the dynamics of contact during such transitions pushes the state-of-the-art in dynamic modelling techniques and tools.

9.0 CONCLUSIONS

Robotics will play an increasingly critical role in the hostile space environment as more and more complex tasks are taken on in the assembly and maintenance of space systems. The MSS fulfils the requirements for the current robotic operations on the international Space Station. Many of the requirements evolve from tasks which are unlike any which have previously been assigned to space manipulator systems. Substantial progress has been made in the design of systems which meet very stringent control and operational capabilities and perform a wide range of tasks in space. To accomplish this, a variety of modes of operation and selectable control features have been designed into the systems for human-in-the-loop and automatic operation. These serve to broaden the scope of operating capabilities of the manipulators and increase their productivity, along with that of the human operators. In the future, even more sophisticated space manipulator systems will be developed as current research in robotics is applied to real space hardware.

ACKNOWLEDGEMENTS

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LIST OF ACRONYMS

ACU	Arm Control Unit
APPC	Arm Pitch Plane Change

AVF	Artificial Vision Function
AVU	Artificial Vision Unit
BDU	Backup Drive Unit
ERA	External Robotic Arm (European)
EVA	Extra-Vehicular Activity
FMA	Force-Moment Accommodation
FMS	Force-Moment Sensor
IVA	Intra-Vehicular Activity
JEM	Japanese Experiment Module
JEU	Joint Electronics Unit
LEE	Latching End Effector
LEU	LEE Electronics Unit
MBS	MRS Base System
MCCF	MSS Computing and Control Facility
MMD	MSS Maintenance Depot
MRS	Mobile Remote Servicer
MSC	Mobile Servicing Centre
MSS	Mobile Servicing System
MT	Mobile Transporter
OEU	OTCM Electronics Unit
OMCS	Operation Management and Control Software
ORU	Orbit Replaceable Unit
OTCM	ORU/Tool Changeout Unit
PDGF	Power Data Grapple Fixture
POHS	Position/Orientation Hold Selection
POR	Point-of-Resolution
PTU	Pan and Tilt Unit
SPDM	Special Purpose Dexterous Manipulator
SRMS	Shuttle Remote Manipulator System
SSRMS	Space Station Remote Manipulator System
VDU	Video Distribution Unit

MISSION, TECHNOLOGIES AND DESIGN OF PLANETARY MOBILE VEHICLE

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SUMMARY

The French space Agency (CNES) started a study in late 1992, of an autonomous rover VAP (for Planetary Autonomous Vehicle). The aim of this study was to investigate multimission mobile platform design. The focus was placed on a martian mission for several reasons:

- there is a very high scientific interest for Mars surface exploration leading to a better understanding of the solar system and Earth evolution,
- roving on the planet is one mandatory and preliminary step before the conquest of the "red planet" by manned mission,
- it is a necessary complement to fixed networks and sample return, in order to get data relevant to very large areas.

The overall system concept including launch, cruise, deboost from Mars orbit, Mars atmosphere entry and landing is not part of the study but is only kept in mind, as these phases of the mission induce several constraints.

The main results of the study are given, showing the two possibilities:
- a large vehicle of 450 kg as the baseline.
- a smaller vehicle of 250 kg as an option.

The various sub-systems are described and the choices justified. The expected performances are summarised.

1- THE REQUIREMENTS

The goal is to design a rover providing the maximum capability for science, devoted to Mars exploration.

The overall system is not part of the study, but the rover must be compatible with an ARIANE 5 Launch and survive the long cruise to the planet. As well, the rover must interface with a descent module and an orbiter during this phase toward Mars.

We have considered the rover is arrived on the martian surface. Then it must have the following mission capabilities: travel 500 to 1000 km. with a rather good knowledge of its position (5 to 10%). This travel is expected to take place in between two dust storms (450 days max.) with possible extension after the wind period.

In detail, the VAP must be able to fulfil three different missions:
- lay down and install three small fixed scientific stations at three different predefined locations on Mars,
- perform geophysical measurements during the move on the planet surface,
- travel as an autonomous laboratory, able to analyse the environment, ground samples, etc...

The vehicle must of course withstand the martian environmental conditions attached to the expected landing site in the "tempered" region of the northern hemisphere: external temperatures between -50°C and +30°C, low gravity (1/3 Earth g.), thin CO_2 atmosphere (less than 1% Earth density). It must also be able to rove on an unknown surface made of sand dunes, quicksands, or hard lava, rocks, boulders, pebbles etc..., climb slopes of 24° and overpass obstacles 0.5 m height. The complete machine will be sterilized to avoid any pollution or contamination of the planet.

Finally VAP must send down to Earth the scientific measurements results, via an orbiter link (high data rate) or directly to Earth (house keeping data).

2- THE INDUSTRIAL TEAM AND BACKGROUND

One of the characteristics of these new robotic systems is the wide collection of techniques involved which implies to set up a complete industrial team having all the various and necessary background.

For this reason, the organization of the study was led by AEROSPATIALE, which has the necessary background and skill for mechanical structure, thermal aspect, integration and system aspect, as usual for spacecraft; but also which has the specific knowledge for atmosphere entry shieldings and protection shells.

The overall electrical system is under the responsibility of ALCATEL ESPACE which has the necessary background and skill for power supply, telecommunication, on-board data processing, and robotic. In this last technique, ALCATEL ESPACE had a strong support from the corporate research center: ALCATEL ALSTHOM RESEARCH which has spent more than 10 M$ on the subject along with FRAMATOME during the last four years, leading to two demonstration models of rovers:
- one devoted to locomotion,
- one devoted to autonomous navigation.

Finally, the robotic activity is completed by a third partner: SAGEM specialized in navigation, localization and sensors for both applications (space and vehicles). Their background and skill is also articulated around a demonstration model, built in a 4 wheel drive vehicle.

3- METHOD OF INVESTIGATION

Two different sizes of vehicle have been investigated:
- a large vehicle of 450 kg. including 125 kg. of payload equipments, able to rove 1000 km during 600 days and to locate itself,
- a smaller vehicle of 250 kg. including 75 kg. of payload equipments, with the same capability if possible.

Presented at an AGARD Lecture Series on 'Advanced Guidance and Control Aspects in Robotics', June 1994.

Looking at the requirements, it is to be noticed that VAP is several things at the same time:
- it is a spacecraft first,
- it is also a robot, which must be able to work alone,
- it is finally a vehicle (like a car) with improved roving capabilities.

The best compromise is to be found in between these functions. For this reason, a permanent iterative process is used, raising new constraints on the subsystems.

Therefore, we think that the output of the study is an adaptative design minimizing the modifications necessary for exploring different areas, or other planets like the moon.

As a consequence of the VAP multiple functions, the architecture study, traditional for ordinary satellites, follows a different approach in that case, because of the displacement of the vehicle :
- the structure must withstand the launching constraints and also those generated by the displacement which induce mechanical fatigue,
- the autonomy must be managed on a day by day basis, and compromises are to be done between the vision, the locomotion, and the constraints coming from the other subsystem as the power supply,
- mixing of traditional subsystem with robotic subsystems implies a real mastering of all the needs in order to optimize the on-board data management resources,
- the degraded modes are studied from the very beginning, as well as the safety aspects, because their impacts on the general architecture could be important.

It is not a satellite which moves, but a vehicle which is to be launched toward an unknown planet.

Therefore, the platform can be split in two different types of subsystems :
- classical subsystems (as for satellites),
- robotic subsystems.

The classical subsystems are :
- mechanical and mechanisms,
- thermal,
- telecommunication,
- power,
- on-board data processing.

The robotic subsystems are :
- perception/navigation,
- autonomous path generation,
- autonomous localization.

The study analyses each subsystem needs in term of energy and data handling capability, in order to choose an on-board architecture which best use the available capability, by means of specialized parts.

During the study several iterations will be made to permanently look for a compromise between the subsystems in order to find the best optimum performances for the vehicle.

A choice for the data management subsystem (DMS) is done from the functional study analysis of the needs, in order to optimize the processing resources. A centralized processing is used as a starting point for this analysis.

4- THE PAYLOAD

No specific work was made on the payload equipments. They are arranged in a way to meet the available place and to cope with the other aspects as thermal, power supply, volume, weight.

Only few characteristics or aspects are taken into account from the payload:
- One concerns the 3 fixed stations to be dropped. They are mounted in locations where the mechanical arm can reach them.
- Another concerns the interaction possibilities with the autonomy of movement of the vehicle. In other word, the following idea has been investigated: it must be very interesting to cooperate with the payload in order to detect gradients for example. As a consequence, such detection made autonomously, may change the mission of the day, to follow the gradient (as water detection for example).

Such payload/system cooperation has been considered as necessary by the scientists in order to improve the capability of founding water on Mars, which is one of the main concern.

5- THE VARIOUS SUB-SYSTEMS

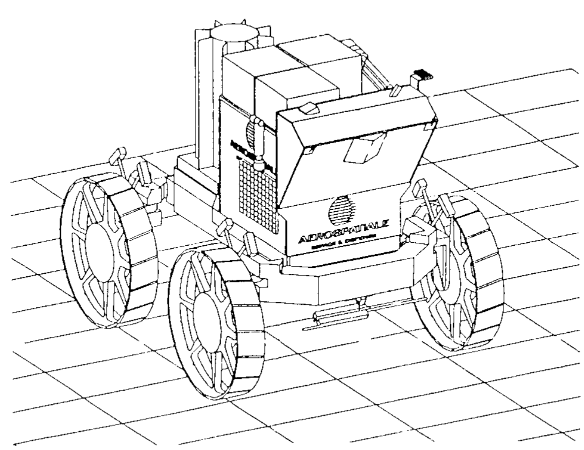
The platform can be split in several subsystems:
- the mechanical chassis with the wheels
- the telecommunication
- the data management
- the robotic, including:
  - mission supervision
  - autonomous path generation
  - locomotion
  - localization and navigation
  - perception
- the power supply
- the thermal control

5.1- THE CHASSIS

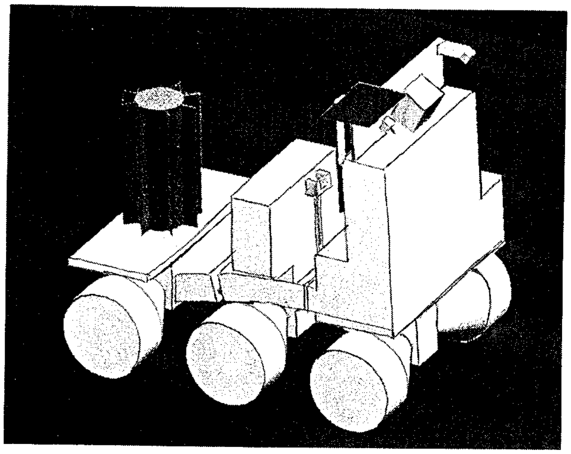
The design of the chassis must meet several requirements which are opposite from each other:
When folded, the volume must be minimum, and when unfolded, the centre of gravity must be as low as possible.
The capability in various terrains depend mainly on the shape of the wheels:
- If they are large it is better for sand dunes,
- if they are narrow, it is better for the total vehicle volume when folded.

Finally in order to get out from difficulties as for example in quicksands, the chassis must provide a "crawling" capability in association with the wheels.

Two different chassis have been designed, one for the large VAP, based on a 4 wheel chassis. The second one for the small VAP has 6 wheels and is rather similar to the Russian Marsokod from the "Mars 96" project. Both of them have the crawling capability (see the fig.).



Large VAP



Small VAP

The large chassis can orientate its 4 wheels in order to turn in place or to stop moving in a slope (brake). Longitudinal sliding rods allow the crawling. A longer vehicle can be obtained by this way which vary the relative weight applied on each pair of wheels. The front axle is passively articulated to the main frame. The wheels are nearly 1 m. in diameter.

The small chassis, can also be lengthen for crawling. The 3 axles are passively articulated to each other. The main characteristics of this chassis are the 3 separated platforms available for the equipments. This small chassis is quite efficient on various terrains: it overpasses obstacles as high as its wheel diameter.

5.2- THE TELECOMMUNICATION

This subsystem has five different missions to fulfil:
- provide a link directly to Earth for teleprogramming of the rover and tranfering operational data. 400 Kbits per day up link and 2 Mbits per day down link,
- provide a link via a relay satellite orbiting Mars for the scientific data. 12 Mbits per day down link plus the direct link capability for back-up purpose,
- provide a back-up mode with lower channel capability,
- provide a permanent standby mode for telecommand access,
- allow to locate the vehicle by mean of the radiometric measurements between the rover, the Earth and/or the orbiter.

The ground space station uses nominally the 34 m diameter antenna from the DSN (Deep Space Network). the 70 m antenna can be used only as a back-up. The use of the station is limited to 1 hour each time (2 hours a day).

The quality of the link is such that the frame error rate is lower than 10^{-5} for 99% of the time.
An hemispherical antenna coverage is enough for all the links from the vehicle.
The chosen frequency band is X band which corresponds to the best optimum.

S band has been rejected because of the too large size of the antenna and also because of the difficulties for VLBI measurements for localization (Very Large Base Interferometry).

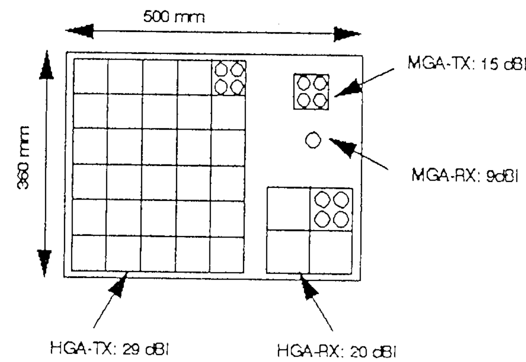
Ka band, on the other side, does not give smaller antenna compared to X band, because of the link availability requested. Moreover S or X band is nevertheless necessary as a back-up to the Ka link which should lead to a mixt complex solution.

Technology of the TELECOMMUNICATION

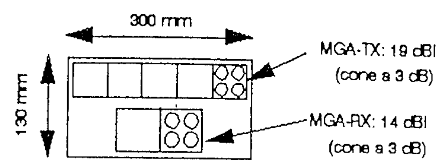
For the X band direct link antenna, the chosen solution is to have a flat antenna electronically steered in elevation, and mechanically oriented for azimuth. The antenna is feeded by 40W SSPA (Solid State Power Amplifiers).

For the relay link, the same kind of antenna is chosen.

Both antenna will be mounted on the same flat support (see the fig.).



Large VAP flat pannel antenna



Small VAP flat pannel antenna

Low gain antenna are also provided for standby mode and back-up mode.
The remaining equipment of the telecommunication subsystem are two X band coherent transponders, a RF distribution unit, two SSPA.

The total mass is around 23 kg for the large VAP for 135 Watts peak during communication (10W standby).
For the small VAP the subsystem can be simplified when considering a lower channel capability for the direct link. The SSPA are only 10 Watts each.
The total weight becomes 14 kg for 50 Watts peak (10W standby).

The procedures of communications are in accordance with the ESA standards.

5.3- THE ON-BOARD DATA MANAGEMENT (DMS)

The functions of this subsystem is to ensure:
- the autonomy of the vehicle in martian environmental conditions,
- the working of the vehicle and the payload,
- the safety when working and the capability to get information back.

The subsystem manages the communications. For this purpose, it controls the direct link and the relay link. The communications are made on appointment (or rendezvous) every day.

This implies:
- the pointing of the antenna according to the ephemeris,
- the set up of back up link if necessary,
- the data processing necessary prior to start the transmission (multiplexing, format set up, storage, etc...).

The DMS performs also the mission control. For that purpose, it keeps the on-board time, manages the high level modes of the rover like:
- starting,
- system configuration,
- mission,
- failure management,
- emergency modes,

in accordance with the various operational constraints and the various phases during the lifetime of the vehicle.

The DMS manages also:
- the lower mission modes according to the daily mission plan loaded every morning,
- the on-board time,
- the vehicle status, and
- the tasks.

The DMS controls the execution of the tasks, by reading the associated scripts, and sends all the necessary commands for that.

Another important function of the DMS is to manage the on-board resources for the other subsystems :
- ON-OFF commands,
- share the available computer time and memory.

It is also very important to know the status of the vehicle. This is the reason why, special attention is placed on this function, performed also by the DMS. For this purpose, several formats are sent back to Earth :
- real time housekeeping telemetry,
- reporting telemetry (from memory),
- upon request from ground: failure investigation telemetry.

The working of the VAP is checked at two different levels:
- A specific function called "supervision" checks that the commands are correctly executed by looking at the equipment status (monitoring information). In case of trouble it turns the system to failure management mode.
- An independent function permanently checks the direct housekeeping telemetry like temperatures, voltages, B.I.T.E. Status (Built-In Test Equipment), etc... This function turns the system to reconfiguration, if necessary.

At the system level, several constraints applied on the vehicle are identified. These constraints were driving factors for the main design choice: The duration of a transmission from Earth to Mars can be as long as 20 minutes one way (40 min. for the answer) which correspond to the greatest distance (worst case). This implies a large autonomy of the vehicle during at least one day. Therefore the commands are high level commands in order to minimize the transmission time. On the other way, the telemetry data, stored during one day, are transmitted according to their relative priority.

Technology of the DMS

The architecture study, has shown that the data management attached to the mission can be separated in two categories:
- the processing relative to the vehicle management and mission control,
- the processing needed for vision, and moving of the rover (path generation and control, stereovision processing).

The first category corresponds to a permanent work of the rover, and needs a medium computing power (2 Mips). The other, at the contrary, is working only during the movement of the rover and needs a high computing power ($\geq$ 10 Mips).

Therefore, two different computers are implemented. The moving processing is chosen to run on a RISC computer (10 Mips).

The remaining processing will run on a MIL-STD-1750 processor (1.3 Mips).

Because of the small communication channel capacity, the operational softwares will be implemented before launch. The non volatile memories will be EEPROM and bubble memory.

The overall DMS sub-system is evaluated to weight 19 kg including 5 kg of redundancy. The power consumption is 35W. and can be reduced to 25W. with a limited redundancy.

For the small VAP, some limitation in the DMS capabilities are envisaged which allows to go down to 11 kg. and 12W.

5.4- THE ROBOTIC

The robotic functions must ensure the missions of the planetary rover and its move.

The main robotic functions are:
- the mission supervision determines the tasks to perform, how to do, and manages the overall functions of the vehicle,
- the autonomous path generation determines in advance which way to take, with only sensors data as inputs,
- the movement control executes the determined movement.

In addition, other peripheral functions must be added as :
- the sensors, which give data according to the vehicle environment or surrounding,
- the localization, which delivers data concerning the position of the vehicle on the planet, and also attitude information.

Some requirements placed on the robotic are coming from the mission :
- The total distance to travel (500 to 1000 km) which imposes to drive 2.5 km per day with only 5 hours of movement in one day. These figures imply to make 10 meters steps with a maximum processing time of 1 minute per step.
- Some of the payload tasks, can have an impact on the robotic functions, in term of time, precision, etc...
- The VAP must be flexible enough to change the overall mission if the first scientific results say so. In addition, some interaction can occur (ex. : to follow a gradient seen by the payload).
- The martian environment is quite unknown. Only a map with 10 meter resolution is available.
- VAP must be autonomous as already seen, because of the transmission delays.
- Finally, VAP must be relailable enough to run correctly during at least 1 year (400 days): neither failure nor accident.

Some requirements are coming from other subsystems:
- Mass and available power supply are limited which imposes to limit the software sizes, the computation time and speed, the memory sizes, some actions are performed in series, instead of parallel.
- Communication rates are also limited. This prevents performant loading of information every day and makes software updates difficult.
- Perception is limited to 1 meters which limits the sizes of the moving steps. The resolution is important too, in order to "see" the obstacles.
- The agility of the vehicle is also important, and its capability to overpass obstacles influences the robotic. More obstacle can be overpass, simpler will be the robotic processing.

5.4.1- MISSION SUPERVISION (decisional structure)

This is the heart of the robotic, always in touch with the data management subsystem (DMS).

It must perform the tasks loaded on-board every day.

For this purpose, the mission suspervision, controls all the elementary functions as:
- Perception.
- Localization.
- Path generation.
- Movement control.
- Payload management.

We have seen above that the DMS must keep VAP "alive", i.e. takes limited actions. On the contrary, the mission supervision allows VAP to be active, i.e. to do what is requested to do. DMS has the priority and can moderate the VAP actions and tasks.

The mission supervision is centralized in the VAP. It knows all what is happening and how is the VAP. Only actions in front of danger are not directly activated by the supervision but automatically triggered by the subsystem which detects the danger.

Through this mission supervision, VAP is programmable:
- at mission level which defines the tasks to performs and the attached constraints,
- at the specification level of the tasks, with the "scripts" which define the cascade of actions and processing for a given task.

The mission supervision receives an error message in case of task failure. This means that for example the movement is stopped, or something wrong appears. The mission supervision can decide to do the same task, but in another way by selecting new scripts.

If the error is coming from a hardware or software failure, a diagnostic is run in order to find the reason why.

Finally, the mission supervision must manage the time constraints associated to the mission plan.

5.4.2- AUTONOMOUS PATH GENERATION

The path generation has two purposes:
- Determine the path necessary for going from one location to the other in order to be closer and closer from the final objectives.
- Check in advance the "safety" attached to the generated path in order to determine whether the move envisaged is safe and without risk.

It is to be noticed that pure reactive methods are not envisaged for VAP as they appear too risky because in this case no feasibility of the movement is checked in advance. The VAP could enter dangerous situation with no return, which is highly probable if the trip is long....

Sensor acquisition and movement are supposed to be made sequentially. Parallel processing could have been retained but was finally rejected for the following reasons:
- sensor precision is worst when moving,
- processing time is not long,
- limited available power supply implies, anyway, to slow down the complete sequence.

The autonomous path generation interfaces with the other subsystems:

The mission suspervision first, which controls the path generation. It receives data also from the localization (position or location, and attitude fo the VAP) and perceptions (distance pictures, and data concerning the ground surface)

The autonomous path generation delivers informations to the movement control (path to follow, locomotion modes, etc...).

It exists several methods to generate a path, which are more or less efficient. The choice has been made on a concept which consists in matching the method to the difficulty of the terrain. This method is the quickest. To three types of ground are attached three different methods for the path generation:

- The so called "1D ground"

If there is just few small obstacles (pebbles) on a surface rather flat, the simplest method is to use directly the data coming from the vision sensors. It is only necessary to check whether to go straight on is valid or not, as a path toward the objective, or to determine a direction in order to head for the objective rapidly.

- The so called "2D ground"

These terrains correspond to obstacles like boulders or small blocks placed on a still rather flat surface. In these conditions it is only necessary to notice what is not "flat" which corresponds to obstacles, and to generate the path turning around those obstacles, but without stability check (when obstacles are avoided, the land is rather flat).

- The so called "3D ground"

For these types of ground, it is necessary to use the general method of path generation : it consists in modelling the land in 3D, and to plan a path in a 3D space, i.e. taking into account the stability of the robot and the spare distance below the robot, for every configuration.

Considering the expected performance of the robot (overpassing capability of 50 cm height, slope of 24°), we have assumed that:
70% of ground are 1D type
25% are of 2D type
5% are of 3D type.

The selection of the method for path generation according to the ground difficulty should bring an important improvement of performances against one method chosen in advance.

The path generation will be made of the following sub-functions:
- selection of the strategy (1D, 2D or 3D),
- modelling: from the sensor data, a flat model is elaborated where the obstacles are placed (2D ground) or a digital model of the ground is elaborated (3D ground),
- local adjustment of the new model inside the known map,
- updating of the map,
- management of the map,
- intermediate target determination,
- path generator (simple if 1D, on flat ground when 2D, on rough areas when 3D),
- moving plan (determine the series of command movements locomotion mode, parameters to look at....).

This last trajectory plan is working on a medium scale representation (the path generation is working on a large scale representation), and is in charge of finding an "a priori" feasible trajectory, that takes into account the kinematics and locomotion constraints.

Performances of the path generation:

Several estimates have been done, leading to the following expected performances:
processing time (assuming a SPARC 2 processor):

- 4 sec in a 1D ground,
- 15 sec for 2D
- 30 sec for 3D

For the small VAP, the approach must be more "reactive" in order to decrease the processing need (speed-power) during most of the moves (70% 1D). The higher levels are kept to the expense of processing time. The reason why is to keep the running of the rover as safe as possible. In addition, the mechanical chassis will help as it is more easy in terms of overpassing capabilities.

5.4.3- LOCOMOTION (MOVEMENT CONTROL)

This subsystem is in charge of the real move of the rover: it uses the chassis of the rover (mechanical structures, wheels, and associated internal sensors).

The chassis generally moves with its wheels (electrical motors). It can move also using it variable length (crawling).

This defines several modes of locomotion, i.e. different ways for following the same path.

All its commands are coming from the mission supervision except the emergency stops which may come from another subsystem in case of reflex actions.

The possible commands always allow:
- to stop and start again a movement,
- to cancel a movement,
- to define a new movement to do.

A movement is fully described by:
- a path mode with describing parameters,
- a locomotion mode (to be used),
- safety conditions.

The safety conditions are tested via:
- either the localization subsystem (stability),
- or the vision sensors (detection of obstacles),
- or the movements and internal sensors (sliding detection, blocking of one wheel, etc...).

This subsystem can be split in several loops:
- one loop determines the moving speed in accordance with the kinematics of the vehicle in order to keep it on the path,
- one loop which directly drives the motors (wheels'speed, and orientation),
- one loop which checks permanently the safety conditions.

5.4.4- LOCALIZATION AND NAVIGATION

The purpose of this subsystem is to have 3 functions:
- to give localization information (where is the rover on Mars ?),
- to deliver stability of the rover (tilt angle with reference to vertical),
- to give navigation information (where is the North, in order to know which direction to take).

For these reasons, this subsystem is composed of several sub-units:
* a star sensor with vertical reference. It delivers the absolute localization of the VAP on the planet,
* an inertial navigation item, which is reset during the VAP steps. It gives the relative localization during the moves,
* a gyrocompass for initial setting associated with gyrometers during the movement. They gives the reference direction in order to known where to head for,
* accelerometers of initial setting associated with the same gyrometers during the movement. They gives the tilt angles of the vehicle (pitch and roll) for stability purpose.

All these sensors are mounted on the structure of the vehicle. There is no stabilised platform. The star sensor is oriented 45° from the vertical.

The overall mass is estimated to be less than 26 kg for 50 W. peak of power consumption during the moves.

The expected performances are the following:

- Absolute position	< 500 m
- Relative position	< 1%
- Relative altitude	< 1% of the move
- Direction precision	< 0.3° always
- Tilt angles	< 0.3° always

For the small VAP, these equipments need to be reduced and the solutions are slightly different:
- A solar sensor replaces the star sensor.
- Only dead reckoning is used.
- Solar sensor and gyrometers for the direction.
- Accelerometers and gyrometers for tilt angles.

In these conditions the performances will be 11 kg for 30 Watts peak :

- Absolute position	< 5 km
- Relative position	5 to 6%
- Relative altitude	< 1% of the move
- Direction precision	< 0.3° when stopped with sun below 80° otherwise : < 1°
- Tilt angles	< 0.3° always

5.4.5- PERCEPTION

The perception subsystem corresponds to the eyes of the VAP. It consist in the association of the sensors with the corresponding data processing in order to deliver information which can be used by other subsystem.

Several function must be performed in this subsystem:

- The 3D perception: this will be done by mean of a wide angle laser range-finder. In addition stereovision is envisaged as a back-up solution.
- The range measurement: it will be done with the laser range finder. The back-up is envisaged with a one-line laser range-finder.
- Nature of the soil evaluation: this will be done with the infrared sensors from the payload.

It is to be noticed that the detailed study has shown the great difficulty to perform the landmark recognition and the horizon profile matching (to be used for the localization purpose).

The main performances expected are the following:

Distance:	10 m
Field of views:	100 deg (2 times 50° range finder)
Total mass:	13 kg
Power consumption:	80W peak (during 2 sec. each time) 0.5W standby

For the small VAP, the two range-finders will be replaced by stereovision for the 3D perception.

The range measurement will be made by a small distance laser range-finder.

The nature of the ground evaluation remains the same, the performances of the small VAP in these conditions become:

Range measurement:	
Distance:	10 m
Field of view:	50deg. (only one range-finder)
Total mass:	6.5 kg
Power consumption:	8 Watts (during 5 sec each time) 0.5W standby

5.5- THE POWER SUPPLY

The power supply of a martian rover must deliver enough power during the complete lifetime (1 year).
After a quick survey on the possible power generators, only two remaining solutions can be envisaged:
- Solar panel.
- RTG (radio-isotop thermal generator).

A rapid power consumption budget for the complete vehicle, shows that the need is very high:
- 250 Watts for the big VAP.
- 60 Watts for the small VAP.

A quick estimate of the solar panel area needed for such level of power forces to reject this solution:

The rover need this power even in the worst case (sun low above the horizon, in winter season, number of daylight hours, panel orientation, etc....) which leads to several square meters of panels. In addition, this solution is also rejected because of the induced problems caused by the possible wind, the dust, and the necessary orientation which will decrease drastically the efficiency.

The only possible solution is therefore the RTG. The power subsystem will be built around such a generator associated with batteries for the peak current. Most of the consumption is dissipated when moving.

A good compromise must be made taking into account all the parameters (which generally influence the power in opposite ways):
- Moving speed.
- Rover capability (maximum slope).
- Ground difficulties.
- Battery size.
- Battery depth of discharge (DoD).
- Battery charge time.
- Peak current.
- Standby power consumption.
- Rover activity (standby, acquisition, localization, vision, move, etc....).
- Time sharing or parallel tasks.
- Etc...

A specifically developed software was used to find the needed compromises, and to notice the influence of several parameters as the battery type.

As an example of the difficulty of the problem is given by the batteries: which battery to choose and what capacity ? Knowing that the DoD (depth of discharge) is not the same for all and that the total weight of the battery influences the power consumption of the electrical motors when climbing a slope.

Finally, the main performances of the power sub-system are the following.
For the large VAP:

- assuming a speed of 0.25 m/sec.:
  RTG electrical power: 189 Watts
  batteries type: Li-C
  battery total capacity: 25 Ah.
  28V regulated bus line

For the small VAP:

- assuming a speed of 0.20 m/sec.:
  RTG electrical power: 60 Watts
  batteries type: Li-C
  battery total capacity: 25 Ah.
  28V regulated bus line

5.6- THERMAL ASPECT

The thermal aspect of the overall vehicle is quite similar to a normal satellite. A complete trade off study has been made on several possible solutions.

Two of them seem to be the best compromise:
- with thermal louvers: they must withstand the Mars environmental conditions (dust, choc) which makes their mechanical design slightly more difficult,
- with phase changing materials: whose main problems are mass and accommodation.

6- CONCLUSION

This study was performed recently, it shows that because of the great distance between Mars and Earth, a very large autonomy is required for a rover to explore the surface of the quite unknown red planet.
Moreover, this requested autonomy seems feasible today thanks to the recent investments made in that field, shown by several demonstration models.
Another result indicates that a great part of the onboard power is dissipated by the motors during the moves, but today, the only possible power generation envisaged is through RTG.

Mars is very far from Earth, but all the problems involved with a vehicle roving on its surface can be solved today. Nevertheless, deeper studies are necessary now if we want to be in time for exploring large areas of the martian ground, necessary to complement the underground studies already envisaged by means of fixed stations.

GUIDANCE AND CONTROL FOR UNMANNED GROUND VEHICLES

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SUMMARY

Techniques for the guidance, control and navigation of unmanned ground vehicles are described in terms of the communication bandwidth requirements for driving and control of a vehicle remote from the human operator. Modes of operation are conveniently classified as conventional teleoperation, supervisory control and fully autonomous control. The fundamental problem of maintaining a robust non line of sight communications link between the human controller and the remote vehicle is discussed, as this provides the impetus for greater autonomy in the control system and the greatest scope for innovation. Whilst supervisory control still requires the man to be providing the primary navigational intelligence, fully autonomous operation requires that mission navigation is provided solely by on-board machine intelligence. Methods directed at achieving this performance are described using various active and passive sensing of the terrain for route navigation and obstacle detection. Emphasis is given to TV imagery and signal processing techniques for image understanding. Reference is made to the limitations of current microprocessor technology and suitable computer architectures.

Some of the more recent control techniques involve the use of neural networks, fuzzy logic and data fusion and these are discussed in the context of road following and cross country navigation. Examples of autonomous vehicle testbeds operated at various laboratories around the world are given.

1. INTRODUCTION

In order to compete with an on-board human driver for anything other than specialist missions, such as mine clearance or materials supply, the unmanned vehicle will need to be capable of negotiating its route to a destination far from the starting point, safely, and at a speed comparable to that of a manned vehicle. The mission may be in a structured environment (e.g. on roads) when it may encounter other static or moving traffic or it may be in a totally unstructured environment (across natural terrain) when the primary task will be to locate, recognise and avoid obstacles in its path.

Whilst artificial intelligence is currently far from solving all these problems in an integrated and cost effective fashion, at the present time it is appropriate to review the progress that has been made in the field and to attempt to predict the advances that can be expected in the future.

An unmanned ground vehicle (UGV) will be operated in one of a number of control modes and it will be convenient, for the purposes of this paper, to define these first as they serve as a useful framework around which to describe the guidance and control technology.

In the basic remote control mode the operator sends to the vehicle, by radio or land line, steer and speed commands. He then views the response of the vehicle directly in the field of view of his eye, or a suitable optical sight, and continues to send command signals to guide the vehicle to its destination. Clearly this will generally only be practicable if the operator has a clear unimpeded view of both the vehicle and its intended destination at all times. This will be a major restriction operationally. It does, however, require only a one way communication link, the data requirements for which are common to the more general case of teleoperation. Here the vehicle is fitted with a television camera and this overcomes the need for the human operator to have line of sight to the vehicle. In this case, the video signal is transmitted from the vehicle and received by the command station where the operator views, on his monitor, the visual scene ahead of the vehicle. The operator then responds by sending the speed, steer and other commands to the vehicle on what is now a duplex communication link. These signals will be of very low data rate compared with the bandwidth required for the video signal. The bandwidth required for a standard TV picture will be of the order of 5MHz or so and it is unlikely that this will be available in the radio spectrum for dedicated operation, unless special provision for line of sight airborne or satellite relays is made. For ground to ground transmission, the high carrier frequency required to bear the video signal is not in general compatible with non-line of sight operation. It is this latter requirement which pushes the communication carrier frequency into the VHF part of the spectrum for radio control. If fibre optic ground links are acceptable from an operational point of view, then the bandwidth restriction no longer applies as multi channel video capacity is easily available.

If VHF carrier frequencies are to be used for teleoperation, then the video signal from the TV camera on the vehicle has to be compressed to a data rate compatible with this frequency band for transmission back to the operator. This compression has to be achieved by carrying out a degree of image processing on board the vehicle. Typically we consider a data link of about 16kbits/sec capacity or less as the link data rate for this lower bandwidth teleoperation. Compared with the 100 Mbit/sec link that is needed for good quality television imaging in the teleoperation mode, this requires a data compression of 6000 to one and will inevitably result in considerably degraded imagery. It can be seen therefore that teleoperation requires a man in the loop at all times, with the corresponding stress associated with the task, and it requires a communication link of high integrity to be maintained.

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The supervisory mode of control seeks to overcome these disadvantages. It requires the operator to have relatively frequent but intermittent communication with the vehicle. Local destination or waypoints are specified by the human operator, and an on-board autopilot navigates the vehicle automatically over the terrain to these destination points in turn. Obstacle detection and avoidance techniques are designed into the vehicle system so that it can navigate safely. The human operator becomes a supervisor, designating the route and overseeing the performance of the vehicle. The reduced operator workload will allow multiple vehicles to be controlled by a single operator.

This is one step towards fully autonomous control which will allow the communication requirements to be reduced to their lowest level. Here the vehicle is tasked with a mission plan in advance and it sets out to implement the plan, using its own artificial intelligence to decide on alternative courses of action, and selecting in turn those most suitable for fulfilling the overall mission successfully.

The human operator, however, still needs to maintain a duplex communication link with the vehicle for the purpose of monitoring its performance, re-tasking, and sending corrective signals to the vehicle if called for in extremis. This autonomous mode of control requires a considerable degree of on-board intelligence with the human operator being involved only in an emergency. Perhaps the most important aspect here is that the on-board intelligence should, at each decision point, generate a highly robust and reliable solution so that the overall mission, which comprises very many such decisions will be successful. It is this search for robustness in decision making which drives much of the long term research in this area.

Fig. 1 summarises the different modes of control in terms of a speculative development timescale and a broad indication of the communication data rates envisaged.

1990	1995	2005	2020
TELE-OPERATION	SUPERVISORY CONTROL	AUTONOMY	
100Mbit/s	16kbit/s	< 1kbit/s	

Fig 1 Development of robotic technology

Having defined the different modes of control we now proceed to address the technical aspects in more detail, reviewing the problems of maintaining the communication link, the minimum data rate requirements, and the human factor issues involved. Considerable attention is given to autonomous control as this presents exciting technical challenges in the fields of computer vision, vehicle control and mission management. The paper ends with descriptions of some of the laboratory test beds which have been designed to demonstrate state of the art performance.

2. TELEOPERATION

The ability to drive safely using teleoperation will depend on a number of factors: the luminance of the scene, the effective resolution and field of view of the optoelectronic system and the effective visual acuity of the operator. It is interesting to compare the potential overall visual acuity of a driver of a manned vehicle with that of a human operator driving a remote vehicle by teleoperation (Fig.2). If we assume that the remote driver is viewing a 30cm high monitor screen at a distance of 50cm (i.e. a subtended angle of 34°) and that the communication bandwidth restricts his display to 625 lines per picture height, then the angular subtense of a single line is about 1 milliradian. The eye resolution is strongly dependent on contrast and the population sample, but a value of 0.5 milliradian is typical for good contrast and luminance conditions, so this is not a limitation. If we compare, therefore, an on board driver with one teleoperating a remote vehicle with unity magnification, i.e. the scene subtense is the same for both drivers, then it does not appear from geometrical conditions alone that the teleoperation is suffering much disadvantage. However, the teleoperator has the optoelectronic system inserted in his vision train and such a system will in fact degrade his image by the modulation transfer function of the optical system, the noise and limiting responsivity of the video camera and electronics, and the interlacing of the display. Care is necessary, therefore, in the design of the system to minimise the degradation in quality of the displayed image. Alternatively, the image quality can be restored by narrowing the field of view of the TV camera but this can be self-defeating as, for safe driving, a good peripheral field of view is essential.

3. THE MARDI SYSTEM

The MARDI demonstrator system is a good example of a teleoperated vehicle and illustrates these general principles (Ref. 1). The remote vehicle was based on a 5 ton tracked platform, one of the family of British armoured reconnaissance vehicles. In order to give a wide horizontal field of view for the driving function, three cameras were mounted in a compartment on the forward edge of the roof of the vehicle each being angled with contiguous fields of view to give an overall horizontal field of 100 degrees. The unit could be controlled in pitch relative to the vehicle to ease the problem of driving in undulating country. It was found that for driving it was the central camera display that was used most of the time, but the peripheral cameras were valuable for turning and maneouvring. As the radio communication system was limited to one full bandwidth TV channel, a multiplexing system was designed to give a reduced resolution image on the central display and a still further degraded image on the two outer displays to avoid exceeding the channel capacity.

From a human factors viewpoint, the object was to give the operator a real feeling of telepresence by providing as many cues as possible to simulate the driving function of a manned vehicle. A steering

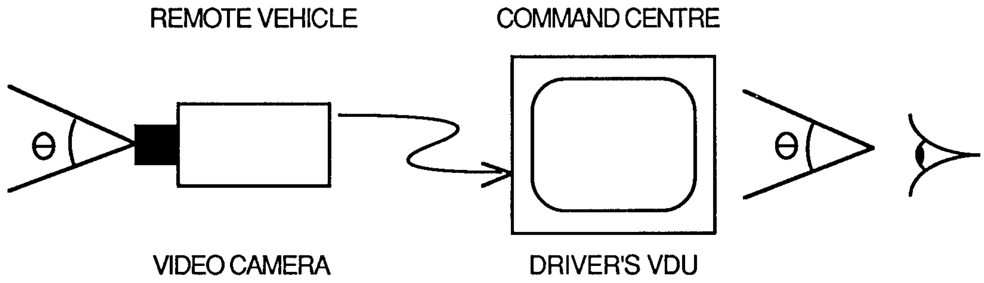

Fig.2 Angular vision for teleoperation.

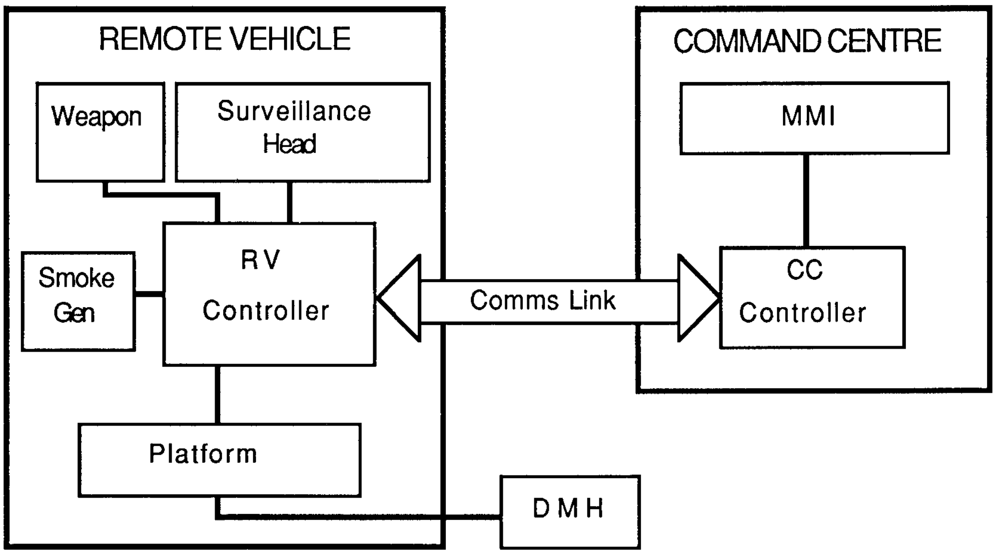

Fig 3 MARDI Control System

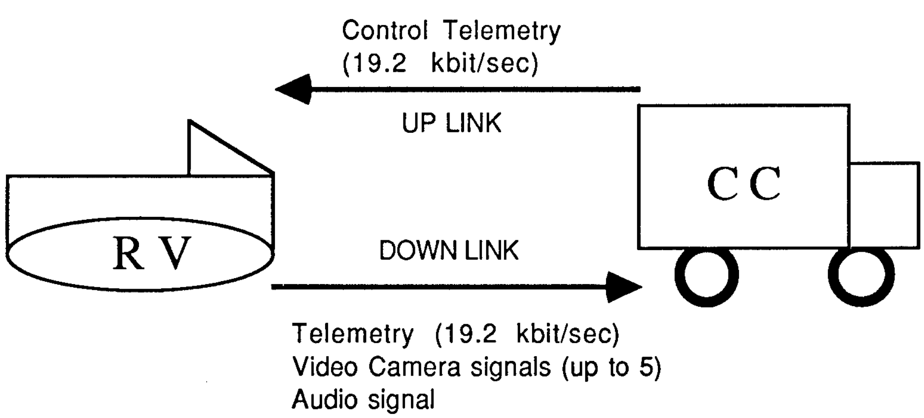

Fig 4. MARDI Communication Links

yoke, accelerator and brake pedals were identical to those used in the Warrior armoured fighting vehicle. A microphone in the driver's compartment of the vehicle was used to give feedback of engine and gearbox noise to the remote driver. This was useful in providing confirmation to the driver that the vehicle was responding satisfactorily to command signals.

An inertial navigation system was fitted to provide both vehicle position and an indication of heading, pitch, and roll angles. The latter were presented as a symbolic overlay on the central display, together with vehicle speed and various warning indications at the edge of the display. The vehicle position was displayed on a digital map mounted above the central TV driving monitor. The map, scaled at 1:25,000, was scrolled to keep the vehicle central on the map. Information on the instantaneous heading and the planned route was also superimposed.

The value of good map information was very evident during the navigational trials This allows potential landmarks and terrain features en route to be prepared beforehand during the mission planning phase. Visibility of these landmarks and terrain features can be anticipated by inspection of the local topography and, during the actual mission itself, this information can be used by the crew (driver and commander) to confirm the correctness of the route. Often the camera viewpoint can be lower than typical manned driving positions, and waypoint data to help guide navigation may be obscured, increasing the chance of the vehicle becoming lost in cross country navigation exercises.

In the MARDI system, apart from a safety operator (necessary for experimental trials) the crew included a driver whose responsibility was to control the vehicle, and operate the payload (e.g. surveillance system) when the vehicle was stationary. The second of the two primary crewmen was the Commander, whose task was to plan and monitor the progress of the mission, and advise the driver on any particular features, obstacles, etc. which he could identify through the use of a panoramic surveillance head during the mission. This surveillance sight was mounted on an elevated mast and, with extra magnification available, this allowed a more detailed appreciation of the surroundings to be obtained than was the case for the driver. However, the system was basically designed for one man operation only, the driver being able to operate all the essential controls himself.

The control system used for MARDI is shown in Fig. 3. The Command Centre comprises a box body mounted on a 4 ton Bedford truck. The Driver, Commander and Safety Operator are seated at separate consoles each with their own monitor displays and controls. Both the remote vehicle control and the command centre control are based on 68020 microcompressors with VME bus arrangements, and they are connected by the communications link which is a selectable fibre optic or radio system. In addition, there is a separate safety system called a Dead Man's Handle (DMH) which operates on a separate radio channel and is capable of disenabling the vehicle if there is an emergency.

The remote vehicle controller operates either to control the platform or the payload under the command of the driver. Modifications were made to the vehicle to make it suitable for computer control. These included an automatic gearbox control unit, a hydraulic braking and steering system, a servo throttle control system and an automatic fire suppresion system. In addition, there is computer control of ignition, starter, and hydraulic accumulator charging system, and feedback of warnings such as low oil pressure are provided. The payload consists of three separate facilities: a surveillance head, weapon system and a smoke generator. The surveillance head comprises a daylight TV and thermal imaging sight and a laser rangefinder. The weapon system comprises a light anti armour weapon training simulator, a chain gun and a laser projector derived from a direct fire weapon effects simulator.

4. MARDI COMMUNICATIONS

The primary communications link between the command Centre and the Remote Vehicle is a single mode fibre optic system (Fig. 4). The system is designed to work over a fibre optic distance of up to 36km but, in practice, the length of cable which can be accommodated on the remote vehicle is the limiting factor. This is 14km for single use disposable cable drums, or 4km for cables which can be rewound after use for repeated operation. A 4-wheel drive Honda motor cycle was adapted for recovery of cable previously dispensed by the remote vehicle. Both disposable and recoverable cables are simply pulled from the (non-rotating) drum by friction with the ground as the remote vehicle moves forward, and this has been found satisfactory up to the maximum speed of the vehicle, namely about 50 kph.

The fibre optic system can transmit five full quality PAL video images from the remote vehicle to the Command Centre together with an audio channel. Also data can be sent in both directions at 19.2kbits/s.

The second communications medium is a microwave link operating at 1.4GHz (down link) and 2.4GHz (up link). A steerable dish antenna is mounted on the Command Centre, and the Remote Vehicle is fitted with an omni-directional whip antenna. The microwave link transmits digital command data at 19.2kbits/sec from the Command Centre, and digitised video, audio and data from the Remote Vehicle, the video being limited to only one full quality PAL image.

5. SAFETY SYSTEMS

Dealing with potentially dangerous vehicles from the viewpoint of the damage which they may inflict if they get out of control, focuses attention on a very important feature of design. The overall philosophy of safety and the impact this has on the design has to be considered at the earliest stages in the project. The scope of such a study has to take into account the collision of a rogue vehicle and any safety aspects associated with the payload such as operation of on-board weapons. The safety system design may well differ between an experimental demonstrator system, such as MARDI, and a

potential in-service vehicle. In the case of the former, safety is of paramount concern in the trials and evaluation of new and untried subsystems. For inservice vehicles their particular role may allow certain safety features to be dispensed with.

At the highest level, for development work on trials ranges, a limited fuel supply system has been installed which ensures that the vehicle will, under all conditions of operation, exhaust its fuel supply before running outside the trials safety area.

For MARDI a dedicated Trials Safety Officer was accommodated in the Command Centre with his own operator's console. This is fitted with a video monitor for camera images, a map display monitor, error displays and system warnings, and an emergency shut down button. The Commander and Driver both have emergency stop buttons to stop the vehicle or halt weapon firing by sending disenabling signals over the up command link. Emergency stop action on the part of the crewmen will usually be in response to indications on the monitor displays which in themselves rely on the integrity of the communications link. In the event of a loss of communications occurring or an unsafe system state (e.g. low hydraulic pressure which supplies the braking system), an automatic computer controlled shutdown is initiated which halts the vehicle or inhibits its weapon system. There is still the possibility of a computer hardware or software fault occurring and, to cover this situation, a computer "watchdog" on the Remote Vehicle will apply the main brakes if faults are detected in this or the communications system (Ref.2).

Up till now all the safety commands have been transmitted via the main communications link between the Command Centre and the Remote Vehicle. This is clearly a potential source of weakness so, again for the purposes of development trials, a Dead Man's Handle has been introduced. It is based on an independent fail safe radio link operated from a manned Land Rover vehicle. In all circumstances, this vehicle stays within line of sight contact of the Remote Vehicle, and the Dead Man's Handle operator maintains the radio link to enable the Remote Vehicle to move under control. The range of safety features may appear excessive, but when little experience exists in the operation of large UGV's caution is wise. As confidence is gained simplifications can be contemplated. The Dead Man's Handle could be operated from the Command Centre itself instead of from a separate vehicle and the limited fuel system could be dispensed with. For the operation of weapons systems a separate set of control procedures is necessary. Currently a keyswitch on the Remote Vehicle has to be enabled to allow arming of the system, and firing the weapon system can only take place after a series of specific commands is received from the Command Centre and the DMH is enabled. Much still remains to be done in this area to optimise the safety system for weapons operation, particularly in conjunction with movement of the remote vehicle where a combination of vehicle motion and the carriage of live ammunition on board poses an additional hazard.

6. COMMUNICATIONS PROTOCOLS

There are broadly two types of data which have to be exchanged between the Remote Vehicle and the Command Centre. These are (1) the relatively high data rate imaging data on the down link with data rates in the range 10kHz to 5MHz and (2) the low data rate control and feedback data on both the up and down links. Radio will provide the most flexible but moreover the most vulnerable means of communication. Channel capacity will always be at a premium and a substantial amount of this capacity will be taken up with error protection to counter interference and jamming. The remainder will be dedicated to the protocol necessary to multiplex and address the real signal data. For any unmanned ground vehicle system, therefore, there is an urgent need to minimise the bit rate associated with both the control data and the protocol overhead. The imaging data tends to be a special case defined by its video nature, whilst the control data may comprise many channels of continuous repetitive data and one shot function operations. We shall now discuss what is involved in minimising the protocol overhead and the quantitative data itself.

Some form of protocol is necessary to arrange the essentially multi-input data into a form suitable for serial transmission and subsequent decoding by computer. The pressures for longer term interoperability and ease of adaptation lend support to the need for standardisation at an early stage. The International Organisation for Standardisation (ISO) is a voluntary organisation formed to promulgate standards. In 1978 a reference model OSI-RM was introduced as a model of a computer communications architecture. Its aim was to promote compatible communications among a wide variety of digital systems and to provide a framework for developing standards. OSI-RM is not a protocol standard. It specifies seven distinct layers (Fig. 5) which define the functions involved in communicating, and protocols have to be developed at each layer. Each layer must communicate with the layer above and below it. For communicating between different systems, it is imperative that each system has identical layers and uses the same protocols.

The bottom three layers of OSI-RM are communication layers, concerned with the transmission of bits and bytes. These layers are hardware dominated. The top three layers are the information processing layers, adding intelligence to the bits and bytes being transmitted. These layers are software dominated. The fourth, or middle, layer bridges the gap between these two sets of layers.

In detail, the Medium refers to the type of channel over which the signal is transmitted, e.g. air, fibre optic cable. The Physical layer covers the physical interface between the devices used to send and receive bits over the medium, e.g. modulating and demodulating the signals. The Data Link layer attempts to make the physical layer reliable, e.g. by bit error detection and/or correction, synchronisation between sender and receiver, and vehicle addressing for multi-vehicle operation. To perform these functions the bits are arranged into frames. These frames add overhead bits which are used to perform the functions of this layer. The Network layer routes data through a network of computers/terminals.

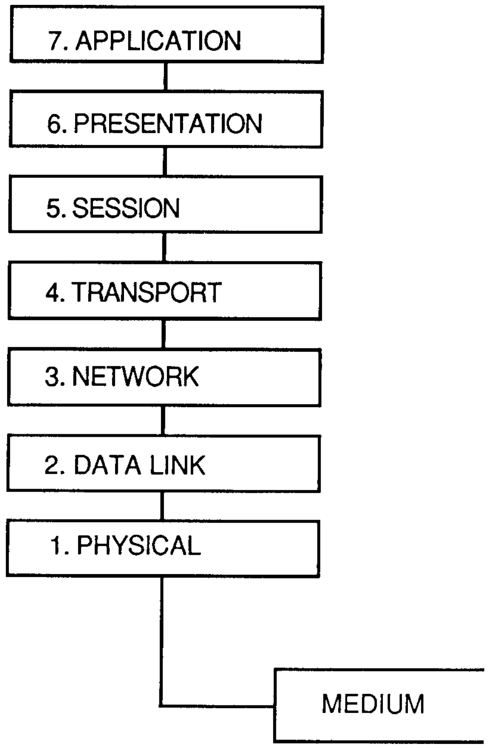

Fig 5 OSI-RM

Initially during development, UGV's will require simple point to point communications and this layer will not be needed. However, when UGV's are fielded in service, networking may well be required.

The Transport layer provides the bridge between the three lower communication layers and the three higher information processing layers. It does for an end to end link what the data link layer does for point-to-point links. The services provided are sequencing, expedited delivery and survival of the connection. The key feature is that expedited delivery is implemented using a three level priority label for the transmission of information packets. The label defines whether an acknowledgement is needed or not. The Session layer provides the mechanism for controlling the dialogue between applications. It provides one of three types of dialogue: full-duplex, half duplex or simplex. It establishes and terminates connections and it allows abrupt or graceful disconnections. In other words, it controls whether a message can or cannot be disrupted in the midst of a transmission, and also the action to be taken if the message is interrupted. The Presentation layer ensures that the information is delivered in a form that the receiving system can understand. This is primarily for providing security through encryption, message compression, and syntax conversion, and is more appropriate for future fielded systems.

The Application layer is to the user the layer which appears to be doing the real work. It describes the bit and byte representations of the control commands and other status information. A common message format has been developed by the US Army Tank Automative Command (Ref.3) specifically for robotic vehicles. This Robotic Vehicle Message Format (RVMF) is in a block format in which each control parameter is preceded by a function identifier. It has the flexibility that different parameters can be sent at different time intervals. The message length is variable. When little or no activity is required, the message length will approach zero bytes. A UGV performing a variety of functions in a complex environment will have a long message length. It also has the advantage that it can order commands by priority. The penalty, however, is that it does require an increased amount of processing. This can be appreciated by examining the overall Message Format which is shown in Fig. 6 and gives the bit numbers associated with each message and submessage. The transaction represents the actual information that is to be transmitted and includes (1) a sequence number to identify the acknowledgment returned against the original message, (2) a transaction type which describes the information type and defines how the recipient should treat the information, (3) the attribute which identifies the control command or the status information that is being conveyed and (4) the parameter itself expressed in terms of the numeric value required, the selection of a particular option, e.g. gear change, or a prescribed action as a function of time. The transaction type comprises the disposition which defines the status/purpose of the command, e.g. initiated and executed, and the category which defines the type of command, e.g. control with or without a requirement for acknowledgment.

The total message length is limited to 128 bytes in order to minimise the latency, that is, the delay between repeated updates of a particular command. A message size of 128 bytes limits the latency time to about 53ms at a channel bit rate of 19.2kbits/sec. But as we shall see later we shall be restricted to much lower bit rates for control data for field worthy systems, and this will correspondingly increase the latency time. We conclude, therefore, that the RVMF is very flexible and suitable for development purposes but may attract an unacceptable overhead for particular systems applications. Current studies are in progress to improve the efficiency of the RVMF and thereby reduce the overhead.

The MARDI system has adopted the RVMF protocol and trials have been carried out to explore the minimum data rate that will allow such a vehicle to be controlled satisfactorily.

In a real time control system, there are three major parameters associated with repetitive commands, namely the update rate, the delay and the resolution. The update rate clearly determines the latency of the command information. On average the system will not receive the information to act on until half the repetition period has elapsed. Delays will be associated with computing time and the response time of the actuation system which is being energised. The resolution defines the precision of the demand which is placed on the actuator system. In controlling a remote vehicle three parameters will be involved, namely steering, throttle, and brakes. With MARDI it was found that satisfactory control could be achieved for these parameters with a resolution of 4, 3, and 2 bits respectively, showing a

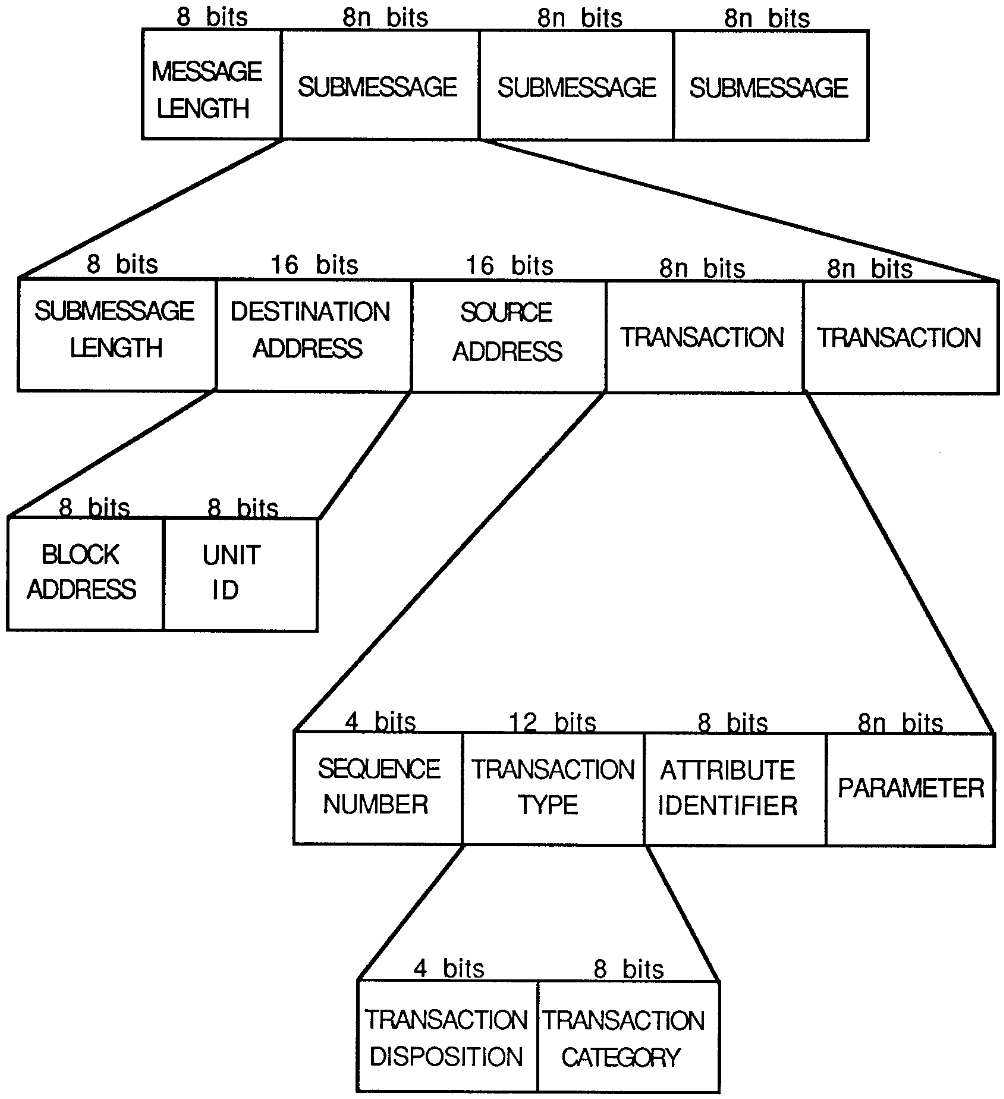

Fig 6 Robotic Vehicle Message Format

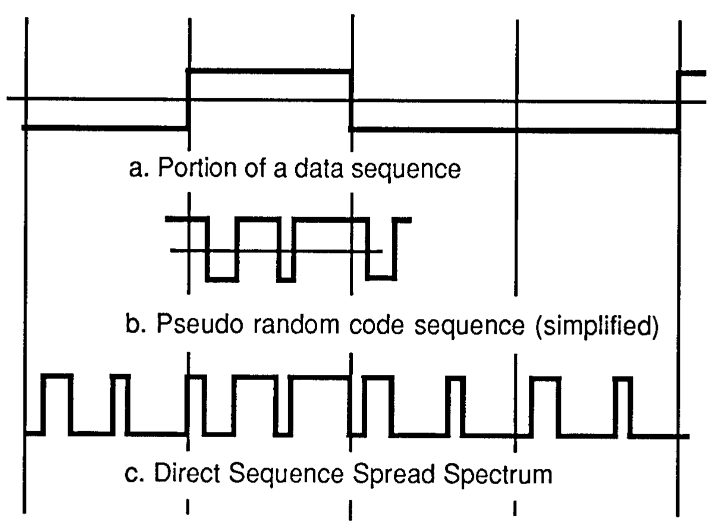

Fig.7 Generating direct-sequence spread-spectrum signals by modulating the data with a pseudo-random code.

considerable reduction on the 8 bits previously used for each parameter. Adding an allowance for other non-continuous control signals such as gear selection, a total driving message of 16 data bits may be sufficient. In order to decode this message a protocol would need to be added to this data. Assuming that a protocol specially tailored to the application is available, a further 16 bits should be added for this purpose, giving a 32 bit message. Error correction to enable the data to be transmitted over a noisy link might add a further 100% giving a total message length of 64 bits. In order to keep the message delay below 100 ms the message must be transmitted in 100 ms giving a transmission rate of 10Hz. Thus we arrive at a command link operating at 640 bits/sec capable of giving an adequate driving performance. This is a considerable reduction on the 19.2 kbits/sec currently being used.

7. COMMUNICATIONS MEDIA

The discussion on teleoperation of UGV's has highlighted the problems of communications as a major factor in determining the range of applicability of such a vehicle concept. We have seen that, apart from communications issues, conventional teleoperation raises no potentially insuperable technical problems. Nevertheless, the difference in data capacity requirements between the up and down links focuses the problem on the down link where full quality video imagery will be demanding bandwidths of the order of 5 MHz. This presents no difficulty for fibre optic systems and we shall consider this in more detail later in this section. But the real attraction of the UGV concept is for untethered operation, and the opportunity for vehicles to range freely at considerable distances (measured in kilometres) from the command centre. It is important, therefore, to review the question of radio communication for UGV application.

7.1 Radio Communications

Apart from data capacity, there is a range of other factors which has to be considered: (1) Path loss absorption effects, (2) Multipath effects which lead to potential interference and fading, (3) Physical dimensions and positioning of antenna systems, (4) Moving vehicle effects (5) Channel spacing and allocation and (6) Detection and countermeasures by a potential enemy. Many of these are conflicting and obtaining an optimum solution will be a complex and difficult exercise. The radio frequency spectrum is covered by a range of frequency bands and these will now be considered in turn.

Very Low Frequency (VLF) For frequencies below 30MHz covering the LF and HF bands, the advantages of non line of sight transmission are outweighed by the non-optimum aerial configuration that will be feasible. Reception efficiency will be optimum when the aerial is a quarter wave length long and, if we assume that a maximum aerial length for a UGV is 2.5m, then optimum reception will occur at 30MHz but will decrease progressively at frequencies below this value. Transmissions can be detected at great distances, even with low-powered transmitters, given the proper ionospheric conditions, and a consequence of this is that video broadcasts could cause interference in locations far removed from their source. Given that bandwidth requirements will occupy a large proportion of the total HF band, it is inconceivable that this band could be used other than for intermittent low data rate communication.

Very High Frequency (VHF) The VHF portion of the electromagnetic spectrum extends from 30MHz to 300MHz. Its principal advantage over other spectral regions is that its range of frequencies is great enough - 10 times the bandwidth of the HF band - and at the same time, the lower end of the VHF spectrum can still provide non line of sight RF. It is, of course, the primary waveband for short range battlefield communications. In the UK, the current inservice combat net Clansman equipment will be replaced by the Bowman system by the end of the century, but the fundamental wave band does not allow for more than 2000 channels each with a bandwidth of 25kHz. Already there is great pressure on channel allocation for established users, and the introduction of a new requirement for UGV's means that dedicated allocation of channels for this purpose will only be resolved on the basis of priorities. There is a move towards digital data transfer for battlefield combat net radios and a data channel will have typically a capacity of 16kbits/sec. This sets a useful benchmark for the data compression of video for teleoperation applications. However, this requires compression ratios of 3000:1 or so and this presents a formidable task for robust digital processing techniques. It involves motion prediction and interframe processing which may well be corrupted by wind and cloud motion in this waveband, since above 30MHz "tropospheric" propagation takes over as the dominant transmission mode, propagation being by space waves within the lower part of the atmosphere (Ref. 4).

Two other effects will tend to degrade the performance in this waveband. The well known "track static" effect, arising from the motion of a tracked vehicle over terrain, tends to reduce the operating range below that obtainable with stationary vehicles. The second phenomenon is that due to multipath effects, whereby reflections from nearby objects, hillsides etc., will lead inevitably to additions to and subtractions from the direct path signal. As the UGV moves therefore, peaks and troughs in the received signal will appear, as well as a gradual reduction due to the direct path loss. These can be expected to occur at quarter wavelength distances. For low data rate control and status signals these effects can be suppressed as the distances will generally be short, e.g. 1m or less, but as we have seen they may be serious for video imaging. Polarisation sensitive antenna and multiple antennae may help to ameliorate these effects.

Ultra High Frequency (UHF) The UHF portion of the RF spectrum extends from 300MHz to 3000MHz offering 10 times the bandwidth of the VHF band. At frequencies above 300MHz the non line of sight advantage of the lower frequency ranges tends to be lost, although at the lower end of the UHF band there is a good compromise between non-directionality and foliage penetration on the one hand, and capacity for video transmission on the other.

Super High Frequency (SHF) This band extends from 3000MHz to 30,000MHz and offers the possibility of highly directional communication links.

At the upper end of the band a 1 metre parabolic antenna can project a microwave beam with approximately a 10 milliradian (<1°) divergence. Because transmissions can be isolated geometrically as well as by frequency allocation, a large number of video transmissions can take place in the same band without necessarily interfering with each other or with other kinds of transmissions. Radiated power levels can be reduced because the transmissions are highly directional. The signals are more difficult to detect and to jam because they are so tightly focused. Also, equipment can be much smaller than at lower frequencies because the wavelengths are so much smaller. The principal disadvantages are that: (1) because of their directionality, relays must be used to circumvent barriers, (2) they are less able to penetrate buildings and foliage/canopy, and (3) they are susceptible to attenuation by rain or fog.

Since UGV's will carry position fixing systems, e.g. a GPS receiver, to provide positional information at all times, and since the locations of control stations will probably be fixed and known a priori, the pointing of the communications antennae can be done with relative ease.

The need for an airborne relay to allow high frequency directional links to operate out of line of sight adds to the complexity of the total systems concept. A simple balloon mounted transponder is perhaps the simplest solution. The balloon would have to be deployed in a covert manner making use of ground topography, woods or buildings. It would not need to be flown near to the command centre, making this vulnerable, but it would have to guarantee line of sight both to the command centre and to the UGV throughout the whole of its mission. An unmanned air vehicle (UAV) is another possibility, but there is an incompatibility between the limited endurance time for the UAV to be on-station (measured in hours) and the long duration UGV missions which could be measured in days.

Extremely High Frequency (EHF) This millimetre wave region extends from 30,000MHz (30GHz) to 300,000MHz (300GHz). Many of the remarks made on the SHF region also apply to EHF but, except for windows at 36GHz and 94GHz, atmospheric absorption is a severe problem, limiting operation to short range applications. The advantages of smaller dimensioned equipment tend to be offset by the expensive circuit technology which is needed at these frequencies.

Packet Radio So far we have considered point to point radio links with or without a single relay interspersed between transmitter and receiver. The advent of packet radio allows a network strategy to be adopted which may have several advantages in field situations. Serial data messages from a computer are attached with routing addresses and error detection codes to form "packets" of data. Each transceiver in the network is configured as a node which allows messages to be forwarded to other nodes only if they are received without errors. The sender of the message needs to know only the nearest node which he has to contact. This node decides on the path to send the message and if one path is not accessible, it will automatically try another path around the network. This can be very useful in a conflict situation where it can be expected that some nodes in the network will be unavailable. Since the length of path segments can be reduced by operating through intermediate nodes, the frequency used becomes less critical as the link distances are shorter. Alternatively, the individual radiated power from each node can be less than if no intermediate nodes are used, which can be beneficial in maintaining covert operation. Inevitably the packet system, with user access at 9.6kbits/sec and carrier frequencies in the VHF/UHF bands, is not ideally suited to real time closed loop control. This is because of delays which may occur in clearing the message through the network and in competing with other traffic. However, for communicating with semi-autonomous vehicles where time is not so critical, the "packet" system may be very attractive.

Satellites The earth satellite should not be ignored as an extreme form of airborne relay. Geosynchronous satellites in orbits 22,300 miles from the earth would impose 0.25 second round trip propagation delays and would hardly be suitable for teleoperated driving. Low earth orbit satellites do not suffer this disadvantage but a constellation of satellites would be necessary to provide continuous coverage, and separate studies are needed for particular theatres of operation. For instance, a two satellite system would be sufficient to provide 100% coverage of all points which are more than 57° from the equator, whilst a 1500km 6 - satellite constellation would provide 90% coverage of the SW Asia region. Another alternative is to add a transponder to the Motorola global cellular telephone satellites. The family of 77 satellites is due to be in position by 1996. Because the satellites will be in low overlapping polar orbits, there will be a need for continuing replenishment and this would provide the opportunity to add a military module or a secondary payload. For such a system data rates will be at a premium with 2.4kbits/sec being typical.

Commercial developments are revolutionising the telephone service by going wideband and all digital, and low data rate videophones are now becoming available. The prospect of teleoperating equipment in whatever part of the world it has to function becomes a possibility, with local cellular networks followed by global satellite links, leaving only RF and/or fibre optic links for the last few kilometres of the transmission. Even today there is scarcely a spot on the globe which is not within CB range of the global telecommunications net, as the recent Gulf War has demonstrated.

7.2 Countermeasures

There will be a need to make the UGV and the command centre with its service crew as covert as possible in order to achieve the battlefield advantage of removing the crew from hazardous areas. Again with the command centre transmitting the lower data rate control signals, this should present less of a problem than the UGV, which can be expected to be physically nearer hostile forces and, for teleoperation, will be continuously transmitting video data. Both problems are, of course, eased if data can be transmitted at high frequencies in focused narrow beams, and the data traffic can be reduced to intermittent exchanges only, by the introduction of partial autonomy.

With electronic surveillance systems now being able to detect and locate VHF transmission in a matter of seconds, attention turns to frequency hopping and spread spectrum modes to give a low probability of interception. Spread spectrum will not be intercepted by the casual listener and encryption/decryption can be used to improve this aspect. As well as these features, spread spectrum can provide resistance to jamming. Frequency hopping involves a conventionally modulated carrier being intermittently shifted in frequency over a bandwidth much wider than the information bandwidth. Typically the dwell time on each frequency will be of the order of 10 to 400milliseconds. It was developed as a counter to narrow band jamming which would be effective if a fixed carrier frequency were used. However, because the peak carrier power at each frequency in the hop sequence is the same as it would be if a single fixed carrier frequency were used, it can easily be detected by wideband surveillance receivers. In fact, the hopping can make the signal easier to detect with such a receiver than would be the case if a single carrier frequency were used, as the latter can be visually masked by other conventional fixed frequency signals operating around the same frequency.

An alternative and more effective approach is to use Direct Sequence Spread Spectrum. This achieves a spreading of the spectrum by modulating the original signal with a very wideband signal (the chip frequency) relative to the data bandwidth. This wideband signal is chosen to have two possible amplitudes +1 and -1, and these amplitudes are switched in a pseudo-random manner periodically (Fig. 7). Thus at each equally spaced time interval, a decision is made as to whether the wideband modulating signal should be +1 or -1. The pseudo random sequence is generated electronically and is know a priori to the transmitter and receiver. The resulting bit stream shown in Fig. 7 is commonly modulated on to the carrier by using 180° phase-shift keying (BPSK) producing a wide-band, suppressed-carrier signal. In all spread-spectrum transmission systems, the receiver has to identify and be able to lock on to and track the transmitted pseudo-random sequences. The simplest approach is to examine all possible phase relationships between the internally generated pseudo-random code and the received signal until a match is found. This is achieved by allowing the two signals to slip past each other, by offsetting their respective clock frequencies, whilst continuously correlating the two signals. Once a correlation peak is found, a code-tracking loop can be brought into action, which will synchronise and track the two signals. As an example, consider 2.4kbits/sec data, which is BPSK modulated. The resulting signal bandwidth is 4.8kHz. This bandwidth is then spread using direct sequence spread spectrum to 15MHz (the chip frequency) on a carrier of a few GHz. This gives a bandwidth spread increase of 15MHz/4.8kHz or 3000:1 (or 35db) which is a measure of the suppression achieved on the primary data signal. It should be pointed out, though, that the bandwidth spread increase will be limited by the maximum carrier frequency that can be used, which in turn determines the chip frequency. The scope for application of the technique will be limited therefore for carrier frequencies in the VHF band. Nevertheless, the technique offers a very attractive method of suppressing detectability of the command centre and of providing jamming resistance.

7.3 Fibre Optics

Many of the problems associated with radio transmission are totally avoided by the use of fibre optic communications systems. Several video channels can be accommodated on a single fibre, full duplex operation is possible over the same fibre system, the source of transmission is not detectable, and there is freedom from mutual interference between channels of friendly forces. Their low weight, high bandwidth, and low transmission loss make them attractive by comparison with wire-cored cable for distances of up to many kilometres. Against these favourable features, however, must be weighed the operational acceptability of reliance on a permanent and probably surface laid cable, whose integrity must be questioned for long distances, and over long periods of time. Although cables have been demonstrated to withstand being driven over by armoured vehicles, showing that very robust protection can be provided by suitable cladding materials, there is always the chance of snagging or fracturing arising at some point in the path. This would clearly render the UGV inoperative unless a back up system were provided to cover such an eventuality. A suitable back up facility might well be supplied by a radio system where, as a secondary or emergency link, its other limitations may make it acceptable in this role. The question of cost cannot be neglected, since at about £1 per metre the dispensing of many kilometres of cable is an expensive item unless the cable can be recovered and used for further missions. Cable is available in two forms. One is a well protected version which can be gathered up after a mission, rewound and then reused. A lighter weight version is prewound on a spool dispenser, wax-impregnated to provide controllable payout dynamics, and is for single operation, single mission, only. Again, there is the option of using the durable version for trials and experimental use, whilst the lighter weight cable could be retained for operational use. Portable equipment is available for carrying out repairs to cable in the field. Fractures can be located by using a laser rangefinder to probe the fibre along its length and reflect off the discontinuity caused by the fracture. Once found, the damaged fibre ends are exposed and removed by controlled cleaving. The two cleaved surfaces are then aligned in a fusion splicer and electric current is used to heat and fuse the adjacent surfaces. A plastic heat shrink with metal strengthening is then used to support the repaired fibre.

Trials of UGV's have been carried out very successfully over a wide range of conditions using a fibre optic tether as the primary communications link, and further details of system options deserve description.

The first choice is between single and multimode optical fibre. The main tradeoff has been optical performance versus ease of connection. The high performance single mode fibre has a small optical core (~ 9 microns) set in a 125 micron diameter silica sheath, and connectorisation requires precise alignment to achieve acceptable loss. Multimode fibres, on the other hand, generally have 50-62.5

micron core diameters, again within a 125 micron diameter outer sheath. The optical performance is defined primarily by attenuation and bandwidth.

Attenuation The attenuation of optical fibre is very near the theoretical limit imposed by Rayleigh scattering, the spectral curve generally following an inverse relationship with (wavelength)^4. Absorption therefore is practically zero over the wavelength range 850 to 1550 nanometres where the best system performance (transmitter/fibre/receiver) obtains. With attenuation as low as 0.2db/km single mode cables can operate without repeaters at distances up to 300km between source and detector depending on the data rate bandwidth requirements (Ref.5).

Bandwidth The bandwidth limitations of a single-mode fibre-optic system arise from dispersion. A pulse travelling down the fibre will broaden due to different spectral components of the optical source having different transmission speeds in the fibre. To maximise bandwidth therefore, we need to select narrow bandwidth sources. Low cost edge lasers (In GaAsP) have a spectral width of 2-5 nanometres compared with 80-120 nm for the high performance Light Emitting Diodes (LED) which are used as a source for multimode fibres. Standard pure silica fibre has a zero dispersion wavelength close to 1300nm and hence narrow spectral sources with peak power at this wavelength should be chosen. However, it is possible to tailor the material of the fibre core to give a zero value of dispersion (picoseconds per nm per km) at specific frequencies up to 1550 nm (dispersion shifted fibres). Multimode fibres have an additional pulse broadening effect due to different optical paths (or modes) within the fibre having different transit times, and this greatly reduces available bandwidth compared with single mode fibres. Multimode fibres (50/125) have (modal bandwidth x km) products typically less than 1000MHz.km. For a teleoperated multi-video system therefore it can be seen that a multimode fibre optic system will limit the cable distance to around 10 km or a maximum operational range of 5km if recovery is intended.

Duplex Link with Single Fibre A single fibre cable allows the simultaneous transmission of optical signals in opposite directions. This can be achieved by wavelength multiplexing or directional couplers. Wavelength multiplexers enable the transmission of two signals, each with a different wavelength, to be combined on to a single fibre. In this way, using 1300nm and 1500nm, or 850nm and 1300nm sources, for example, a duplex link can be set up. A single wavelength single fibre duplex link can be constructed using 2-way directional couplers. These are passive and have the property that power is split between 2 fibres in a predetermined ratio, normally 50:50. The disadvantage is that 5db of additional loss is introduced and reflected power with the system leads to increased noise.

Signal Multiplexing and Modulation Methods used in conventional electrical systems can equally well be applied to each optical channel. These include digital Time Division Multiplexing (TDM) and subcarrier Frequency Division Multiplexing (FDM). FDM is suitable for applications involving multi-analogue video cameras. Amplitude or frequency modulation of subcarriers requires only simple analogue modulators followed by a combiner or mixer. The broadband signal is then used to amplitude modulate the laser or LED source. Often digital data channels have to be multiplexed with other analogue channels. In a subcarrier FDM scheme carrying video bandwidth data channels, digital data can be used to modulate a separate video subcarrier. It is the top end sub-carrier frequency and its modulation products which set the bandwidth requirements for the optical link, and need to be taken into account in the overall link design.

We have seen that the optical performance of a single mode fibre optic system will place little restriction on the communication requirements for teleoperation. But the physical size and robustness are more questionable. For comparison, a dispenser coil to accommodate 20km of fibre will weigh 5kg for 0.5mm diameter fibre, or 34.4kg for 1.5mm diameter (Ref.5). The 0.5mm diameter fibre is for applications where working tensions are low (<1kg), but when these are higher, the fibre is reinforced by poly-aramid yarn and results in the diameter increasing to 1 to 1.5mm. Having installed the dispenser coil on board the remote vehicle and subsequently dispensed the fibre, the question of protection of the surface laid fibre remains. In some terrain situations, it is possible to cut a narrow furrow as part of the dispensing mechanism and then lay the fibre within the furrow, even compacting it afterwards for increased security. The other problem to be overcome is the manipulation of fibre during vehicle maneouvres, especially in confined spaces, when the possibility of self-snagging becomes serious.

8. LOW BANDWIDTH TELEOPERATION

We have indicated the need to reduce the bandwidth of the imaging data fed back from the UGV to the Command Centre in order to ease the requirement on the communications system. Ideally this should be compatible with the control data rate and 16kbits/sec would appear to be a significant target to aim for. A full frame video image is defined by gray level (8 bits), pixel number (625^2) and frame rate (25/s) giving 78Mbits/sec. To reduce this to 16kbits/sec would require a compression ratio of 4900.

Clearly substantial reductions in bit rate (4 bits), pixel number (128^2) and frame rate (10/s) could give a compression ratio of 125 without anticipating a major impact on performance. But there is still a shortfall of x40 in the compression ratio required. Trials have been conducted both at fullscale and in simulation to test the sensitivity to frame rate and pixel number (resolution) in particular. Broadly the speed at which the UGV can be driven is dependent on the frame rate in the range 25/s to 1/s as this determines the ability of the driver to control the vehicle accurately and to trace the route ahead. In one particular trial over unfamiliar cross country terrain, a maximum speed of 45kph achieved at a frame rate of 25/s was reduced to 25kph at 8/s. Reducing the pixel number from 625^2 to 128^2 was not very significant, although it increased the stress on the driver in looking out for obstacles in the path. On the other hand, the pixel number could be reduced, whilst preserving the resolution, by presenting the image in "letter box" format, rather than the full frame picture, by dispensing with the

upper part of the image which is of little value for driving purposes. This exhausts the relatively simple techniques for increasing the compression ratio, and we must now examine how image processing might be applied to make further improvements.

Techniques may be described under two main headings (i) intra frame processing and (2) image sequence processing. The intraframe approach can be tackled either from a spatial or frequency domain viewpoint (Ref.6).

Intraframe Spatial Processing (a) Predictive coding (DPCM). This approach has been studied for the past 40 years, and relies on a prediction of a particular "element" being made on the basis of nearby picture elements. The difference signal is then efficiently quantised and coded. It is possible by developing algorithms of this type to achieve 1 bit/element.

(b) Vector Quantisation (VQ). In this case the image field is divided into small blocks and each is, in turn, compared with similar entries in a codebook. For the closest match, an index corresponding to that entry is sent to the receiver (which also has access to the codebook) which then uses the same codebook entry for reconstruction. Problems hinge on the adequacy, the construction and search of the codebook.

(c) Segmented Coding. Many simpler pictures can be considered to consist of areas of slowly varying luminance, colour or texture, separated by well defined edge detail. The technique involves segmenting the image and then representing the detail with suitable approximating functions. It is the accurate coding of the boundaries which presents a problem here.

(d) Pyramid and Wavelet Coding. This involves the decomposition of image detail into sub images having graded resolution. The original image is low-pass filtered to generate a reduced resolution image at the next level, and this operation is repeated as desired. This structure is the "Gaussian" pyramid and its function is to act as a prediction for the previous higher resolution step. More recently there has been the introduction of "wavelet" structures having localised spatial and frequency domain properties.

(e) Fractals. This has affinities with VQ but an important difference is that the equivalent of the VQ codebook need not be known to the decoder. Results seem to indicate ¾ bit/element to be achievable.

Intraframe Frequency Domain Processing
(a) Transform Coding. The spectra of most "natural" images are strongly low pass, and a suitable transform such as the Direct Cosine Transform DCT, will therefore produce a set of coefficients where high "frequency" terms are usually small or even zero. Significant coefficients are scaled, quantised and transmitted, and an inverse transformation at the decoder reproduces an approximation to the input. If extreme compression is attempted, block structure artefacts appear and this adds to the stress on the operator.

(b) Sub-band Coding. This has a close affinity with the wavelet techniques. The image is split into a number of separate frequency bands for coding and transmission. The reconstructions at the receiver are then summed to produce the output image. Sub-band coding has about the same performance as Transform Coding and is well suited to progressive transmission and multi-resolution applications.

Image Sequence Processing The dimension of time provides another means of coding compression. If only the <u>changes</u> in the interframe sequence are transmitted then considerable savings in data traffic can be made. This is particularly effective in the case of teleoperated driving where changes occur mostly in the foreground where the computer power needs to be deployed, rather than in the upper part of the image, covering the more distant scene which is relatively invariable.

(a) Three dimensional techniques. These can be extended to two dimensional predictive coding, transform or sub-band coding. Multiple frames are stored and an adaptive switched predictor operates on the basis of local image activity.

(b) Hybrid Coding. Here an interframe prediction step produces an error image frame which is then subjected to further (spatial) processing.

(c) Model Based Coding. Image analysis techniques can yield parameters which when transmitted to the decoder, can be used for the resynthesis of the image. Given a particularly constrained image scene such as a road or track, a "Wire Frame" model, used in conjunction with texture mapping, might allow an acceptable representation. Location of, and tracking information on, changing features are sent to the receiver as updates. The transmission rate may need to be only a few hundred bits/sec depending, of course, on the number and rate of the changing features.

9. CODING TECHNIQUES

For any data transmitted over a communication link there is the possibility of corruption due to noise or, in the case of a radio link, interference or fading. Coding techniques will be required to provide error detection and correction to ensure that the receiver deals only with uncorrupted data. This will be particularly important for low bandwidth systems where the degree of redundancy in the data is minimal.

Fig. 8 illustrates a simplified communication system. The source (transmitter) sends a message, via the

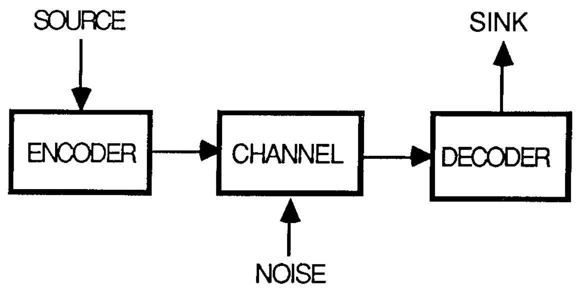

Fig.8 Simple communication system

encoder, across the channel, where the encoded message might be corrupted by channel noise. The message then passes into the decoder where, hopefully, the corruption due to channel noise can be eliminated, and the correct message passed to the sink (receiver).

The decoder takes the received word and compares it to every acceptable codeword to find the "distance" between them. The "distance" is the number of places (bits) in which two words differ. It finds the minimum distance between the received word and a codeword. If there is only one codeword which is this distance from the received word, then the received word is decoded as this codeword. If there is more than one codeword this distance away, the decoder cannot decode the received word. The minimum distance between codewords 'd' gives the code's error correcting/detecting ability. Simple coding theory shows that the number of detectable errors is (d - 1) and the maximum number of correctable errors is $\leq$(d -1)/2. Thus a code word of only 5 bits, with a minumum distance of 4, can correct one error and detect up to 3 errors.

Coding theory has generated various types of codes each effective under different conditions. The choice of code therefore will be very dependent on the type of channel noise expected.

10. POSITION FIXING

Before leaving teleoperation it is worth reviewing the role of position fixing in the control of the remote vehicle. So far it has been sufficient for the operator to have position data supplied on line to him for the purpose of assisting him in recognising waypoints en route, and in determining "distance to go" to the destination. In general, whilst knowledge of the remote vehicle position is essential to the operator to avoid the vehicle becoming lost, the accuracy need only be sufficient for this purpose. It will be determined by the quality of map information available, and the density and visibility of waypoints. Heading to 0.5 degree and position to 100m may be acceptable for this "advisory" role. This may be achieved by gyroscopically based inertial navigation equipment, but a less expensive dead reckoning system using a heading reference and odometer sensing may be adequate for shorter range vehicles, where the operator can zero the on board system when he arrives at recognisable waypoints. The key point in the teleoperation mode is that the position fixing sensor is not working within the guidance and control loop as is the case with supervisory and autonomous control. In these latter modes of operation, the vehicle position accuracy will be determined by the achievement of success or failure in the mission, measured in terms of the vehicle position. In other words, it should be commensurate with the ability of a manned driver to position the vehicle safely, for example, to prevent the vehicle accidentally leaving the road and ending up in a ditch. In relative terms, therefore, with reference to the actual position of the vehicle, obstacles will need to be located to perhaps 10cm. In absolute terms, i.e. with reference to the local mapping information, accuracies of 1-20metres will be required if significant errors in navigation are to be avoided.

Global Positioning Systems The advent of the Global Positioning System (known as GPS) has provided the basis for a highly accurate system capable of measuring the position of any point on the earth's surface to within a few centimetres. Based on 6 constellations, each with 3 satellites, in different orbit planes around the earth (the expensive part of the system), a receiver on the user vehicle becomes a small and relatively inexpensive unit which can nevertheless extract the positional data at incredible precision. (Ref.7) The satellites all transmit continuously on the same frequency of 1575MHz and a method of separation and identification is required, as data from 3 satellites have to be received to give a 2D fix and from 4 satellites for a 3D fix. In addition, the carrier frequency chosen gives rise to an ambiguity every 20cm. The application of spread spectrum modulation (Fig.7) solves these three problems simultaneously. The code (the C/A code) runs at 1·023MHz and has a length of 1023 bits. By giving each satellite its own code, many satellites can co-exist without interference and each may be individually identified. In addition, the satellites' own position and transmission times have to be known since the positional information in each plane relies on time delay ranging between two satellites at a time. This information is provided by a further level of modulation. Correction to the satellite position to allow for transmission delays is handled by each satellite transmitting the equations of motion of its orbit. In addition to the C/A code, each satellite transmits a precise code, known as the P code, which is reserved for the military. This operates at a chipping rate ten times faster than the C/A code giving a ten times wider bandwidth and therefore greater jamming resistance (see Section 7.2). The P code signal can also be changed to another code in times of emergency to give antispoofing protection. From the user viewpoint there remain two difficulties. Firstly, the availability of sufficient satellites at an elevation which enables the high accuracy to be maintained. This will be optimised when the target number of satellites, namely 21, is finally placed in orbit in 1995. Secondly, the visibility of satellites to the UGV due to the screening effects of buildings, trees etc. These effects are likely to force the user to fit some independent position fixing system to cover the situations when the GPS is not available to the UGV.

Whilst GPS is basically a position fixing system, recent developments using multiple antennae on a ground vehicle, have enabled heading information to be derived when the vehicle is moving or stationary. By mounting antennae at a spacing of, typically, 1 metre azimuth accuracies of 0.2-0.4° have been obtained.

11. SUPERVISORY CONTROL

We have defined this mode of control as intermediary between teleoperation and autonomous control. It assumes the man is not an integral part of the control loop, and that he provides only intermittent information on new waypoints or alternative routes for the UGV. The essential element is that the vehicle should be able to implement an unintelligent path to a distant waypoint whilst travelling at a reasonable speed and arriving with acceptable positional accuracy. In the first instance we shall

assume that the terrain is reasonably flat and obstacle free. The MARDI system, described in Section 3, was adapted to demonstrate the principle of supervisory control in a cost effective way. To avoid hardware changes in the remote vehicle itself, a single supervisory control unit was designed as an interface unit installed in the Command Centre where it communicates with the Main Computer through shared memory. The Commander enters future waypoints as icons on his map display, which also presents the current position of the UGV via the feedback data from the inertial navigation equipment. The Supervisory Control Unit then translates the path to the first waypoint into a series of heading and speed demands which are transmitted along the communications link to the UGV, just as if a human operator were physically manipulating the control functions for normal teleoperation. In order to do this, of course, the Supervisory Control Unit has to have built in a model of the vehicle control system to ensure that the vehicle is not asked to carry out impossible demands, and yet will perform the necessary maneouvres by making optimum use of steering, throttle, brakes and gearbox controls.

The system was exercised in a field environment and successfully demonstrated that it could reach two waypoints 50-100m apart, the second requiring a heading change of 90° from the first. This was carried out using the appropriate gear selections and with speeds up to 10kph. The success of the Supervisory Control Unit design would naturally lead to its removal from the Command Centre and the incorporation of a similar system in the UGV itself, thus reducing traffic on the communications link to the Command Centre to tell-back data and position coordinates of the waypoints alone. It should be emphasised that the above only refers to "blind" driving. It has taken no account of land topography or obstacles and simply attempts to implement a straight line path between designated waypoints. Adding an obstacle detection capability would then require an automatic means of obstacle negotiation and this leads logically into fully autonomous control. If we assume, for the purposes of Supervisory Control, that the human operator takes responsibility for route finding, waypoint marking, and obstacle detection, then some low bandwidth video display would be suitable for these functions to be performed. This was the basis for the first Computer Aided Remote Driving (CARD) system developed by JPL in the US. The operator designated a route on his video screen and this route was transformed to the ground plane (assuming a flat ground) and then transmitted to the UGV for the vehicle autopilot to implement. Route planning was essentially carried out on a still frame, although stereo cameras were fitted to the vehicle to give some range perception, but the concept was essentially a "stop-go" routine. The most distant point would be limited by the clarity of the video displayed image and accuracy would suffer at these limits of visibility.

Feed Back Limited Control System (FELICS)
An alternative approach, demonstrated by Dynamic System Technologies Inc. in the US in 1992, attempts to optimise the speed at which a manually designated route can be negotiated. The operator has control of a cursor or "puck" which can be moved around over the video display generated by the camera which is pan and tilt mounted on the UGV. This camera is slaved to point in the direction of the "puck". The "puck" is moved by the operator to trace the most advantageous route towards the eventual destination, and as it does so it spawns waypoints along the route at 1 metre ground plane spacing. The UGV now drives itself automatically through these waypoints in turn, following at a safe distance, i.e. an appropriate stopping distance, behind the "puck". If route planning for the "puck" becomes difficult, the Operator switches the camera to panning mode and this automatically inhibits the spawning of further waypoints, the UGV coming to a halt at the last designated waypoint. Successful navigation was achieved with the system operating at 1 frame/sec on a 300kbits/sec data link and operation at 1 frame in 3.5sec was also demonstrated. The UGV camera was mounted high on the vehicle to give a good depression view of the path ahead, but nevertheless, the number of waypoints on the screen was never greater than about ten which implied a relatively short "look ahead" distance of 10m. This tends to confirm that the degraded video display associated with the low bandwidth teleoperation will limit the ability of the human operator to plan routes ahead over significant distances within his field of vision.

When the vehicle autopilot takes sole responsibility for navigating between waypoints, it is important that the designated step length equals the actual distance to be traversed over the ground. Normally a flat ground plane is assumed, but ground slope variations between the local vehicle position and the designated waypoint position will lead to significant errors in the demanded step distance. Ideally, this can be measured directly and eliminated using a boresighted laser rangefinder to measure the exact distance to the designated waypoint, but the group at Carnegie Mellon University in the US is investigating alternative ways of reducing the errors arising from this source, by measuring the local ground inclination of the vehicle with the on board navigation system at the latest possible time, and using this to correct the position of the next waypoint. This they have termed the STRIPE technique (Ref.15).

12. AUTONOMOUS CONTROL

In the supervisory mode of operation, we have assumed that man is available to deal with the more difficult route planning and image understanding tasks, and systems have been described which show that such systems can already be built and demonstrated in a field environment. The ultimate objective scientifically is to show how these tasks can be carried out by machine intelligence, and we need to review the current state of technology and philosophy in order to establish the boundaries of current achievement, and our expectations for the future in this complex and challenging area.

12.1 System Architectures

Fundamental to our understanding of the problem is our ability to represent the operation of an intelligent autonomous vehicle in some logical and structured form. There are essentially two forms of architecture in use or in development at the present time. Firstly,

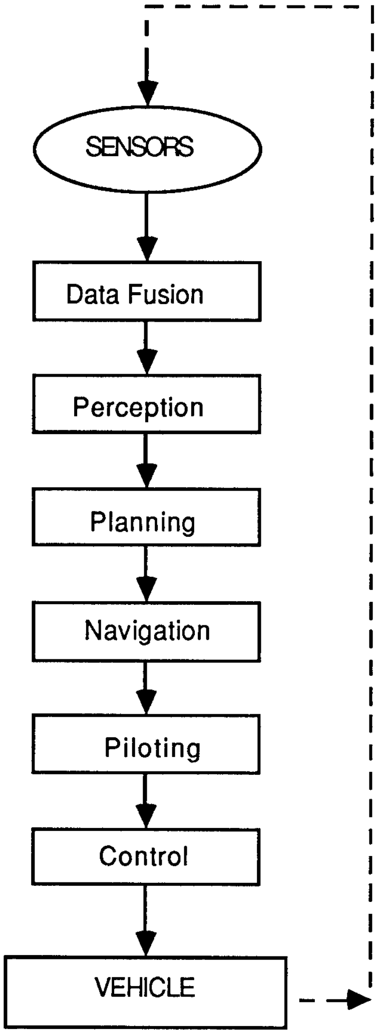

Fig.9 Functional Decomposition

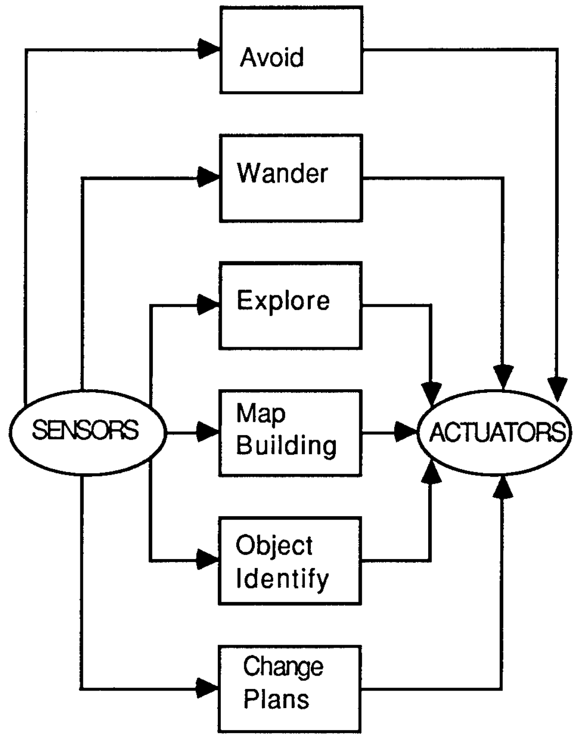

Fig.10 Behavioural Decomposition

there is the Functional Decomposition (Fig.9) in which the robot is considered as a group of processes, known as agents, each carrying out a specific function. The agents are usually the perception system, the planner, the navigator and pilot, and the executor or controller. The second structure is the Behaviourist Decomposition (subsumption architecture) (Fig.10) which considers the robot to be composed of levels of behaviour (avoid, wander, explore etc.) such that there is only performance degradation instead of total system failure when one of the higher levels fails. Additional layers of intelligent behaviour may be added later increasing the overall "competence" of the system (Ref.8).

NASREM Functional Architecture The US National Institute of Standards and Technology (NIST) has attempted to generate an open system (platform independent) control architecture for real time advanced autonomous robotic systems that is functionally based, and which incorporates many of the features of current research projects (Ref.9).

This has developed into the National Standard Reference Model Architecture (NASREM) and is shown in Fig. 11. It is hierarchically structured with six layers each performing a different fundamental transformation on data. It is also partitioned horizontally into three sections, task decomposition, world modelling and sensory processing. The flow of commands and status feedback is hierarchical. Goals are decomposed both spatially and temporally throughout the different levels, with each task decomposition node on a given level receiving input commands from only one higher level supervisor node and outputting to a set of lower level nodes. Data is shared horizontally between modules, with much higher horizontal data rates than vertical data rates. The architecture is structured to allow evolutionary growth in capability and autonomy, with comprehensive human-computer interaction (HCI) acting through a global memory management system. The six general levels of functionality are now described, starting at the lowest level. Level 1 - Actuator or Servo. This level transforms any motions and positions expressed in a generalised coordinate system for the mission, e.g. the start point, into coordinate systems more relevant to particular vehicle sub-systems, and sends appropriate control signals to the vehicle effectors [Sample rate 1kHz, replan time 1 ms]. Level 2 - Primitive or Component. This level computes vehicle dynamics with respect to an appropriate generalised coordinate system and sends vehicle control commands to ensure that the desired trajectory within this coordinate system is followed [Sample rate 62Hz, replan time 16ms]. Level 3 - Elementary (E) Move/Subsystem. This level performs a piecewise decomposition of elementary move commands into a series of intermediate motions

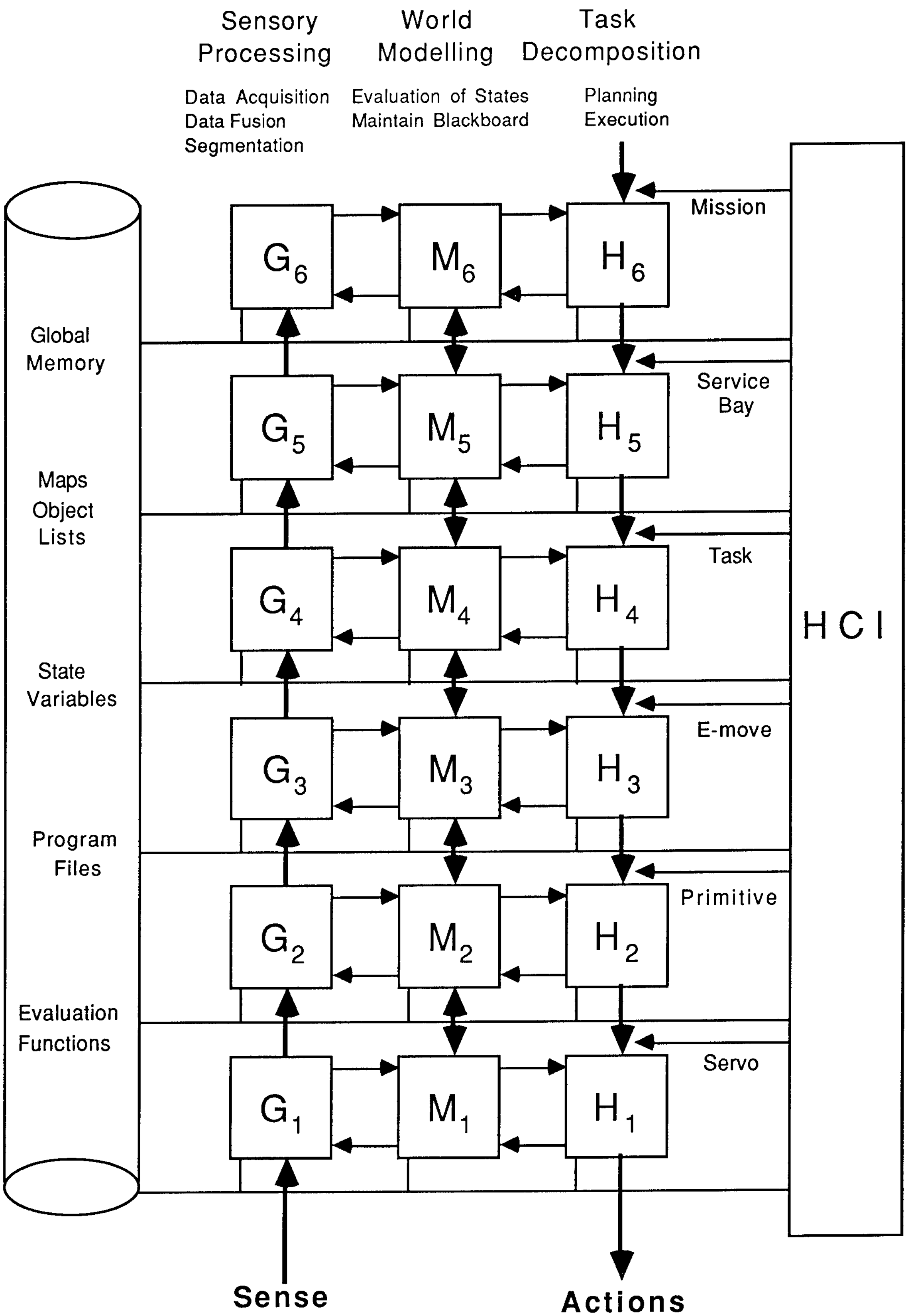

Fig.11 The NASREM Hierarchical Architecture

and positions. These intermediate motion commands define a path which has been checked and is clear of potential obstacles, and can be physically implemented by the vehicle [Sample rate 8Hz, replan time 128ms]. Level 4 - Task/Robot Subsystem. This level decomposes object tasks into appropriate sequences of elementary moves defined in terms of elementary vehicle manoeuvres or subsystem motions. An object task is one which must be carried out by a single sub-system or on a single object. It also coordinates the start and stop scheduling of elementary moves and the scheduling of any coordinated sub-system activity [Sample rate 1Hz, replan time 1s]. Level 5 - Cooperating Robots/Service Bay. This level decomposes complex tasks involving operations on a number of objects into tasks carried out on single objects [Sample 0.1Hz, replan time 10s]. Level 6 - Mission/Groups of Robots. This level decomposes an overall vehicle mission plan into action commands. The mission plans would usually be generated by humans off-line and specified in terms of mission goals, priorities, requirements, constraints and overall mission timescales. [Sample rate 0.01Hz, replan time 1.7min].

One area of particular importance is safety and, in order to prevent the vehicle performing undesirable actions or entering undesirable states, a separate safety system using redundant sensors and a completely separate data base may be necessary.

NASREM aims to define a set of guidelines which can evolve into applicable standards for the design and implementation of a wide range of autonomous, semi-autonomous and teleoperated systems, subsystems and components.

Behavioural Architectures In this architecture the control task is broken down into a hierarchy of behaviours or "competences", each of which selectively assists or assumes (subsumes) the control functions of lower behaviours. Each control level is built incrementally on top of the last tested and debugged control structure. Strictly speaking, the layers are built from modules that are finite state machines which can communicate with each other via simple protocol, narrow bandwidth links. Modules can inhibit the output of other modules and suppress input to a module whilst substituting its own data in place of the suppressed input. This mechanism enables one layer of modules to add behaviours and extend the behaviour of the lower levels so that the total set of behaviours is greater than before. Low level high priority safety behaviours are simple to ensure rapid response. More complex, less critical mission specific behaviours, such as map building or scene reconstruction, are layered over the safety behaviours. The significant point is that low level survival behaviours do not have to wait or interact with more complex behaviours. Contention between multiple parallel behaviours for control of an actuator is resolved by hierarchically layering the behaviour. In practice, the capacity of individual modules is soon overloaded and considerable effort is necessary to prioritise supposedly parallel finite state machines. In order to allow easy and rapid reconfiguration of the control structure, both during and in between missions, an augmentation of the architecture is necessary. By applying state configured control the structure is simplified and the number of behaviours active at any time is reduced. Initially, a state transition diagram related to the desired mission is constructed indicating the behaviours which need to be operable during the various stages of the mission. A layered control structure associated with each of the states in the state transmission diagram is then generated.

Both functional and behavioural control decompositions have their advantages and disadvantages. The behavioural decomposition and state transition layer are essential in the design of the control strategy, whereas the functional or hierarchical decomposition, which is required at every behavioural level, is important in the physical realisation.

Beyond this basic architectural philosophy are the longer term goals of achieving interoperability, extensibility (to new components) and scaleability (to increasingly complex systems). Work is currently aimed at an Open Command and Control Reference Model (Ref.10) and is based on the NASREM functional model. It concentrates on the organisation of a distributed intelligent sensing system allowing the hardware and software to be treated separately and flexibly. With the emphasis on modularity and productivity of hardware and software, the opportunity for much greater commonality of thinking and cooperation becomes apparent, and will hopefully provide the impetus for the generation of standards and reference protocols in this area.

12.2 Control Techniques

Having set the scene to give an overview of the total system navigation task, it is helpful to focus on the very practical problem of controlling the vehicle platform itself. The two basic configurations are wheeled and tracked. The fundamental difference arises in the method of steering in the lateral direction. The wheeled vehicle achieves this by articulating the front wheels, whilst in the tracked arrangement, a skid-steer procedure is typically adopted which involves differentially powering or braking the respective tracks. For the purpose of this discussion, we shall concentrate on the wheeled vehicle concept taking as an example the ROVA vehicle (Ref. 11). This is a fourwheeled Camper Van developed as an autonomous road following test bed by the Defence Research Agency in UK. The 3.5 ton vehicle is equipped with an automatic gearbox and is modified for computer control by the addition of servo actuators for the steering, accelerator and service brakes. Television cameras for vehicle guidance are mounted on a steerable head and view the scene ahead through a windscreen located above the normal driving position. The control approach is that described by Dickmanns (Ref.12) which uses model-based control to recursively combine prior knowledge (in the form of dynamic models) and current measurements, to estimate the motion state of the vehicle and states describing the road geometry which act as a constraint on the vehicle motion. This method is computationally efficient, provides an established treatment of measurement and system noise, allows the selection of well conditioned measurements (and conversely the rejection of outlying measurements) and provides system state information as a function

of time. The scheme may be expected to work satisfactorily when the system (i.e. vehicle and environment) is sufficiently well structured to be described adequately by relatively simple models. We can assume that the vehicle is relatively invariant and unchanging with time, whereas the environment is likely to present, even in a road scenario, a wide range of potential road boundaries, junctions, obstacles, traffic etc. which will tend to complicate the road scene model. Fig.12 illustrates the control scheme used. For correct driving, the vehicle control system must maintain the television image of the road boundary at a specified position in the image. In the basic concept the lateral location of the nearside road boundary is tracked by two windows in the television image of the road ahead of the vehicle. Measurements from the near windows are used by a model based steering controller, which incorporates a Kalman state estimator, to derive a steering demand, u_c, which maintains the vehicle motion (position and heading) within safe limits on the road. Measurements from the more distant windows are used to update a Kalman state estimator to provide a measure of road curvature. For adequate control bandwidth, the road boundary measurements are made at half frame rate giving a sampling period of T=80ms. The road curvature estimates may be used for vehicle speed control. An additional anticipatory control block ensures that the optimum vehicle motion can be predicted when the vehicle moves into a curve. The general form of the steering controller is shown in Fig.13. If it is assumed that the vehicle (plant) is moving on a plane straight road, then, applying small angle approximations, the open-loop vehicle motion at a given speed may be modelled by 5 linear equations in the state vector $\mathbf{x}^T = (\psi,\beta,\theta,p,\delta)$ where,

- ψ = vehicle yaw rate
- β = sideslip angle at the centre of mass
- θ = vehicle body heading with respect to the road
- p = lateral displacement of the vehicle on the road
- δ = front wheel steer angle

In standard discrete time the open-loop motion is modelled by:

$$\mathbf{x}(k+1) = \Phi\mathbf{x}(k) + \Gamma u(k) + \Gamma_1 \mathbf{w}(k) \ldots \quad (1)$$

where,

- u = control input
- $\mathbf{w}$ = plant noise disturbance vector
- Φ = plant transition matrix representing the plant dynamics
- Γ = input distribution matrix
- Γ_1 = noise distribution matrix
- k = time in units of the sampling period T

In this particular representation the output from the plant y, is the measured location of the road boundary in the image plane. This is obtained by forward perspective projection and, making small angle approximations, is linearly related to the states, thus

$$y = H\mathbf{x} + v \ldots\ldots\ldots\ldots \quad (2)$$

where v is the measurement noise and H the measurement matrix which depends on the camera parameters and the measurement geometry.

All 5 states of the vehicle are estimated from this single measurement y over time, using a standard Kalman filter;

$$\begin{aligned} \mathbf{x}(k+1|k) &= \Phi\mathbf{x}(k|k) + \Gamma u(k) \\ y_e &= H\mathbf{x}(k+1|k) \quad \ldots\ldots \quad (3) \\ \mathbf{x}(k+1|k+1) &= \mathbf{x}(k+1|k) + L(y-y_e) \end{aligned}$$

where L is the gain of the filter and $\mathbf{x}(k+1|k)$ is the state estimate at time (k+1) based on measurements up to and including time k. y_e is the estimated value of y at time (k+1). L depends on the relative magnitudes of the plant and the measurement noise. The vehicle compensatory steering demand u_c is computed by state feedback

$$u_c = -K\mathbf{x} \ldots\ldots\ldots\ldots \quad (4)$$

where the control gain matrix K is chosen to achieve a satisfactory closed-loop time response.

The open-loop vehicle dynamics are speed dependent so that in equations (1) - (4) the plant transition matrix, control and estimator gain matrices are also speed dependent. In ROVA, these matrices were precomputed for a range of speeds in a design stage carried out off the vehicle, and stored in look up tables which were addressed according to speed when the vehicle was under automatic control.

Control and Estimator Gains The s-plane locus of the poles and zeros of the open-loop system are dependent on the vehicle speed. There were 3 fixed poles at the origin, corresponding to 3 integrations which arise in the vehicles equation of motion, two fast poles (which decay rapidly with time) on the negative real axis and a real zero relatively close to the origin. Suitable values of K were pre-computed off-line using both pole placement and by optimisation of a cost function. In the optimal approach, the cost function shown in eqn (5) was minimised subject to eqn.(1). Thus I, a scalar measure of the performance of the control system, is given by:

$$I = \sum_{k=0}^{N} [\mathbf{x}_k^T Q_1 \mathbf{x}_k + u_k^T Q_2 u_k]\alpha^{2k} \ldots\ldots\ldots \quad (5)$$

The parameter α allows bounds to be placed on the settling time of the closed loop system. The settling time, and the weight matrices Q_1 and Q_2 were chosen to achieve a balance between dynamic response and the control effort required. Q_1 and Q_2 allow varying degrees of weight to be placed on the contribution of the states $\mathbf{x}$ and the magnitude of the control signal u. For a computed step function response to a demand for a new lateral location on the road, an acceptable rise time and overshoot were obtained over a range of vehicle speeds. The Kalman gain matrix L (steady state) for the vehicle state estimator was computed using assumed values for the measurement and plant noise contributions.

Road Curvature Estimation Road curvature is estimated using road boundary measurements made further ahead of the vehicle in conjunction with a geometric road model. A Kalman filter is again used to obtain an optimal estimate. Account must be taken of the vehicle motion state as this contributes

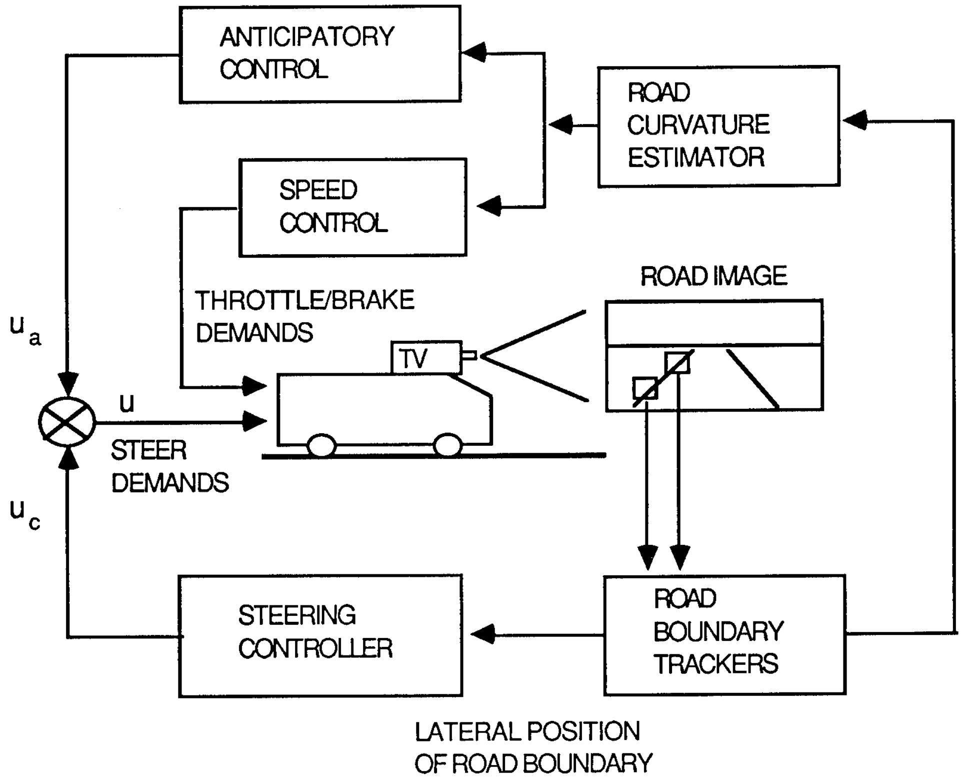

Fig.12 Schematic of the ROVA Control System

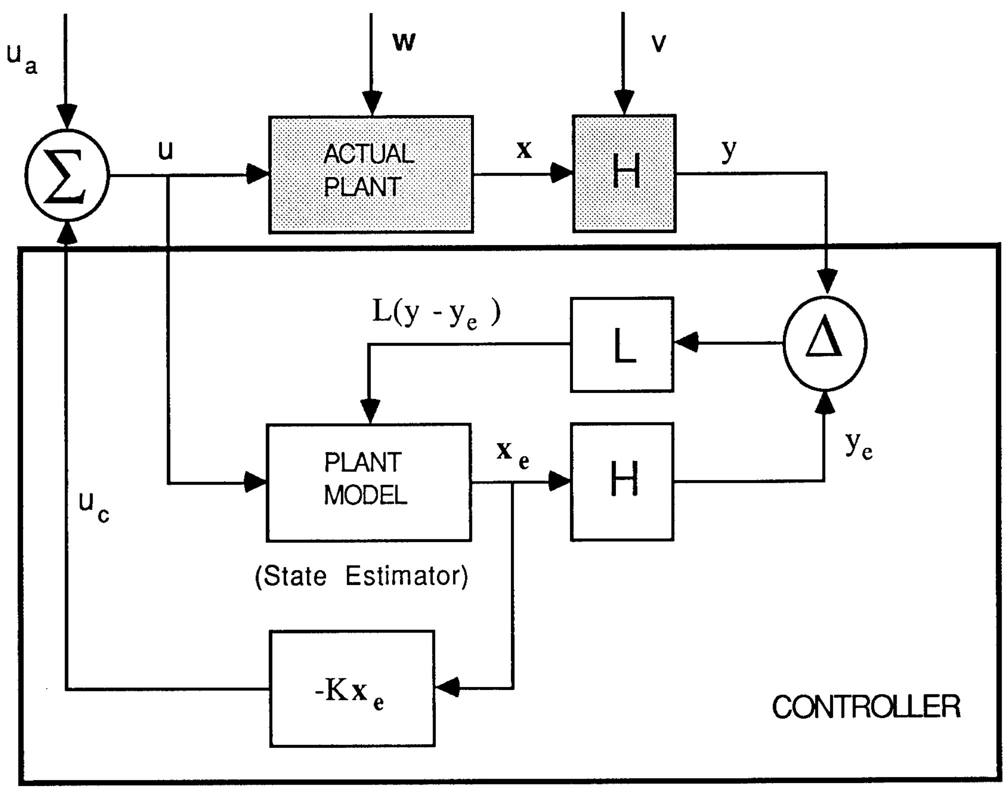

Fig.13 General Model-Based Controller

to the measured location of the road boundary in the tracking window. Similarly when the vehicle is moving on a curved road, it is also necessary to include curvature terms in the vehicle's equations of motion, and to regulate the system about new set points. This is achieved by the anticipatory control block in Fig.12. In addition, the curvature estimates are passed to the vehicle speed controller, to regulate the vehicle speed according to the road curvature.

Speed Control Closed loop speed control is achieved by a PI controller whose parameters were estimated experimentally. In operation, the vehicle is commanded from the system console to accelerate at a given rate to a final desired speed, subject to a maximum value determined by the local road curvature.

Control System Simulation To test the control system design and software prior to control of the physical vehicle a real-time closed loop simulation was developed. The real world road-view was replaced by a computer graphically generated view of the edges of the road, and the vehicle itself was represented by the dynamic model given in eqn.(1). Each road edge was obtained by integration of the Frenet-Serret equations for a plane curve. The control cycle time used was 80ms as in the real system. Each near view of the road was obtained by integration of the lateral (eqn.1) and longitudinal equations of motion of the vehicle with a time step of 10ms, followed by projection of the road view into the image plane. The road location was measured in the image plane with new road position information injected at 80ms intervals, and a steering demand signal was input to the vehicle model to maintain the correct motion of the vehicle with respect to the road. The simulation was carried out using a computer generated circular road of varying curvature and road width, and establishing the vehicle performance over a range of vehicle speeds and distance from the road edge for different values of K and L. By carrying out sensitivity checks in this way, the number of vehicle parameters which had to be measured experimentally was minimised. The simulation was executed directly on the vehicle's transputer machine to ensure direct applicability and to reduce the need to rewrite code. 16 transputers were used in the overall system simulation, 6 being dedicated to the vehicle dynamics and road generator, which were not required when the vehicle was driven live.

Control System Design Procedure The following summarises the sequence of operations which were found necessary in the development of the ROVA control system.

1. Model the Plant. Derive the equations of motion in terms of appropriate state variables.

2. Discrete Time Plant Matrices. Choose the sample time of the digital control system and compute the matrices Φ, Γ and H from equations of motion.

3. Pole Placement Routines to compute Feedback Gain K and Estimator Gain L. To ensure stability and achieve desired time response under the range of chosen conditions, e.g. speed, Kalman estimation can be used to determine L depending on the relative influence of plant and measurement noise.

4. Reference Demand. Allows choice of the control system set point, e.g. lateral distance from the road boundary.

5. Time Response Computation and Display. Examine the time response of the system in simulation (non-real time) to changes in the set point. If unsatisfactory, repeat procedure from Step 3 until the performance is acceptable. Investigate sensitivity to changes in Φ, Γ and H.

6. Control Parameter Data File. Collect together all speed dependent elements of Φ, Γ, H, K, L and the reference demand into a look-up table for use by the vehicle controller for autonomous driving.

7. Real Time Simulation. Run the system over a test course to confirm software integrity.

8. Experimental Trials. Confirm expected performance in autonomous driving with the real vehicle system parameters Φ, Γ and H.

12.3 Application of Fuzzy Logic to Control

Classical control techniques, like the model reference approach, result in precise deterministic performance at the expense of the complex formulation of dynamic models. The development of fuzzy logic attempts to reverse this trend by generating pseudo qualitative methods which rely on finite and generally small numbers of outcome values formed as a result of combinations of limited quantised input parameters. Take as a simple example a vehicle travelling along an obstacle free corridor (Ref.13). Given the object is to centre the vehicle motion along the centre of an initially linear corridor, a rule structure has to be set up to define two condition variables, the heading relative to the corridor, and the distance from the corridor centre line. The lateral pilot has to produce an output which is the desired vehicle path curvature. Thus if the heading is A_i and the offset distance is B_i then the desired curvature is C_i. The fuzzy set definitions for this corridor regulator are illustrated in Fig.14. The input variables are classified as being large, medium or small, positive or negative, or zero. A triangular membership distribution μ using intuitive limits on the values is chosen with a non-linear distribution around the origin to provide increased sensitivity. Thus seven fuzzy sets are used on the two condition variables, leading to a possible 49 rules. These are collapsed to 11 possible outcomes using a verbalisation technique, i.e. by describing the actions of a human driver in this rule format. By adding the measured path curvature at a fixed distance ahead (the look ahead distance) to the output of the corridor regulator, path guidance can be generated for small, constant curvature corridors. Reducing the corridor width demands a tighter vehicle response and correspondingly higher maximum path curvature demands. Having generated an obstacle free path, it is the task of the longitudinal pilot, whilst satisfying vehicle safety and lateral acceleration constraints, to determine the vehicle's speed along the path. This requires inclusion of the vehicle's dynamics which are usually parameterised by speed as well as environmental

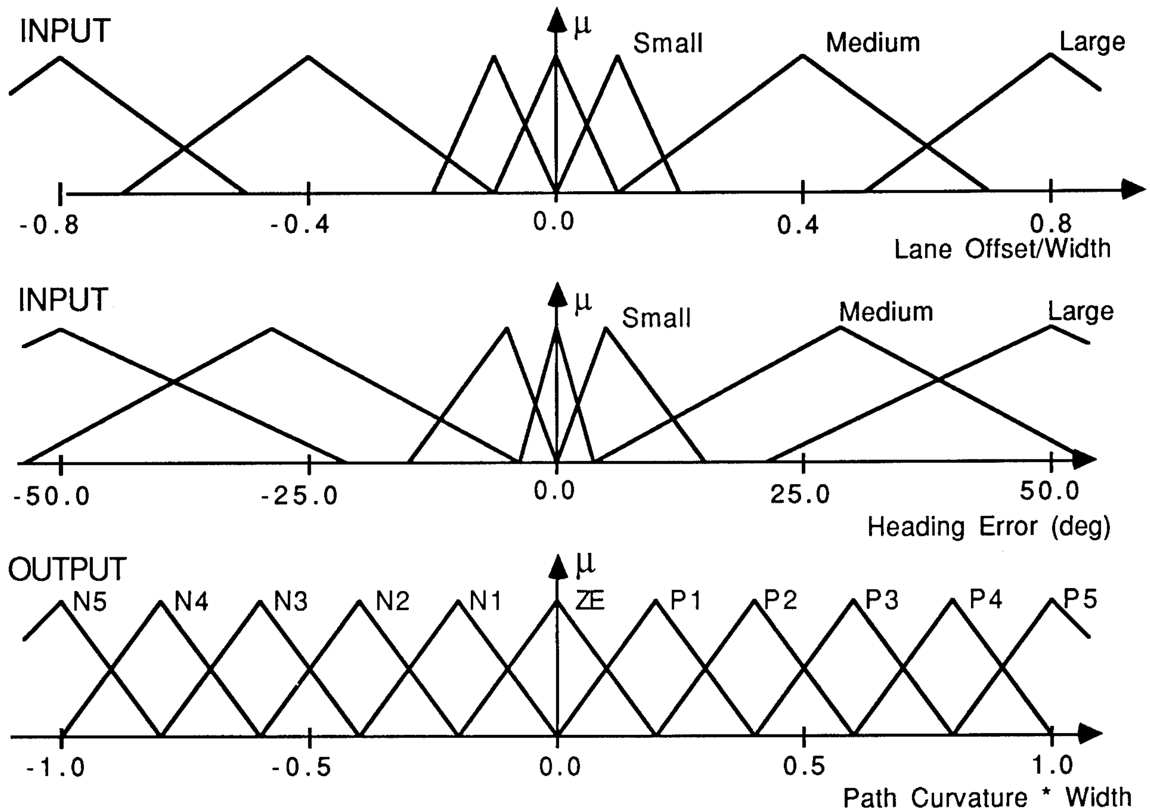

Fig.14 Fuzzy set definitions for corridor regulator

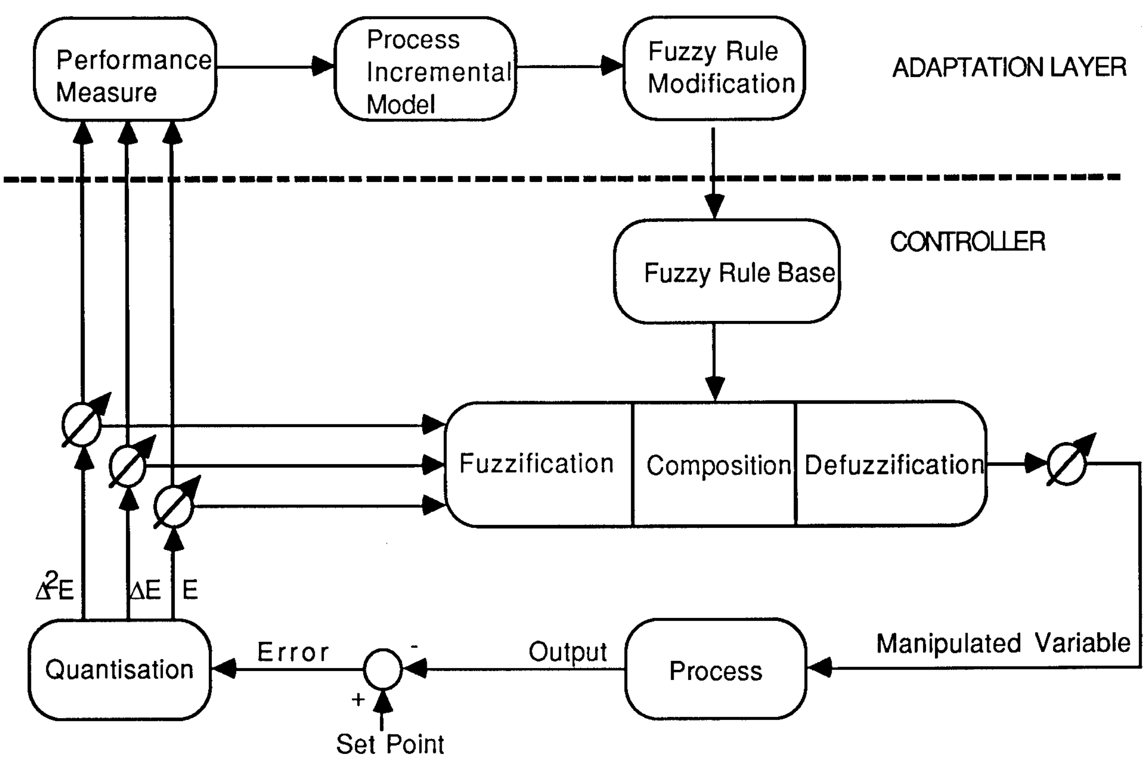

Fig.15 The Mamdani self-organizing controller

conditions such as road adhesion. This procedure provides, therefore, an alternative approach to the simulation previously described for the model reference system applied to ROVA.

So far we have described a static fuzzy logic controller which is robust and adept at dealing with complex or poorly defined dynamical systems, but it offers no on-line adaptation to reflect changes which may occur in the controlled process or its interaction with the environment. The adaptive fuzzy controller overcomes these problems by performing on-line adaptation of the controller rule-base. These adaptive controllers can, if sufficiently excited, produce a complete rule-base, replacing inadequate or faulty rules. The most widely used technique is the self-organising fuzzy logic control introduced by Mamdani which, as with any learning system, requires a performance measure/index against which the achieved response can be evaluated. This can then be used to generate a feedback signal to alter the control policy. In this way, a self-organising controller is able to improve its capability based purely on experiential means, with little or no a priori knowledge of the process being necessary. The Mamdani controller is illustrated in Fig.15. The systems break down into two levels, the controller and the adaptation level. The controller level is identical to that used in the static fuzzy controller, described earlier, with the rule-base supplied from the adaptation level. The adaptation level uses a performance table to drive a rule modification process. A typical performance table in terms of error and error rate is shown in Fig.16. A central band consists of desired combinations of error and error rates which require no further adaptation. Regions away from this desired band generate an adaptation signal which determines the direction of the rule adaptation. The rule modification process involves identifying the rule which causes poor performance (usually by selecting the rule which was used at a fixed time interval in the past) and applying the modification required by the adaptation signal.

The following summarises the attributes of adaptive fuzzy logic controllers:

1. the ability to control systems with little a priori plant knowledge.

2. fast adaptation to large unmeasured plant parameter changes.

3. effective operation in the presence of a mismatch between plant order and controller rule structure dimension.

4. control of plants with stationary non-linearities.

5. good noise and disturbance rejection capability.

6. probable convergence for fuzzy plant modelling (under strict technical conditions).

Unfortunately, the memory requirements for fuzzy logic controllers grow exponentially with the dimension of the system variables used in the control rule-base. However, it is possible to structure rules for a static fuzzy controller in a hierarchical or nested fashion to reduce the number of rules for complete cover.

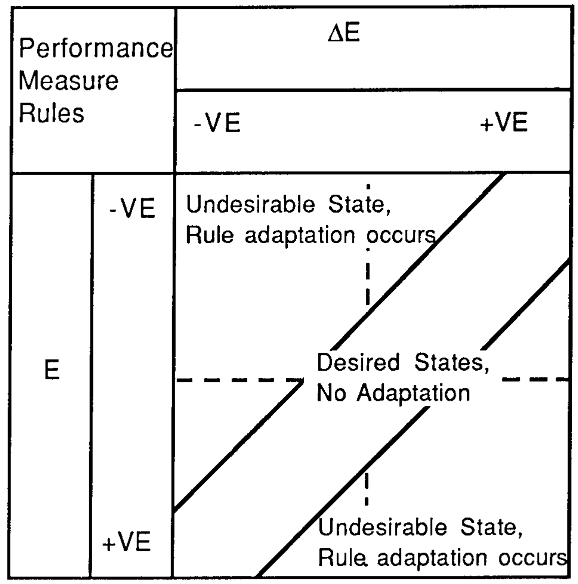

Fig.16 A typical performance table for a self-organizing controller.

12.4 Artificial Neural Networks for Control

Artificial neural systems can be designed to imitate rules of behaviour that permit them to function autonomously in a work space, after they have been trained to respond correctly to a set of situations which spans the range of those likely to be encountered. The training can be provided manually, either under the direct supervision of a system trainer, or indirectly using a background mode where the network assimilates training data as the expert performs his day to day tasks. Artificial neural systems are networks which consist of a number of processing elements interconnected in a weighted, user-specified fashion, the interconnection weights acting as memory for the system. Each processing element calculates an output value based on the weighted sum of its inputs. In addition, the input data are correlated with the output or desired output (specified by an instructor) in a training exercise that is used to adjust the interconnection weights. In this way, the network learns patterns or imitates rules of behaviour and decision making. The Multilayer Perceptron (MLP) is one variant of an artificial neural network which has been found suitable for many applications (Fig.17). The input and output layers of nodes are connected by one or more intermediate or "hidden" layers, and each interconnecting link is associated with a weighting value. One of the early examples of an artificial neural network (ANN) was one designed to drive a robot vehicle down a simulated highway in traffic (Ref.14). The fully developed highway simulation consisted of a two lane highway having varying straight and curved segments. Several pace cars moved at random speeds near the robot vehicle. The network was given the tasks of tracking the road, negotiating curves, maintaining safe distances from the pace cars, and changing lanes when appropriate.

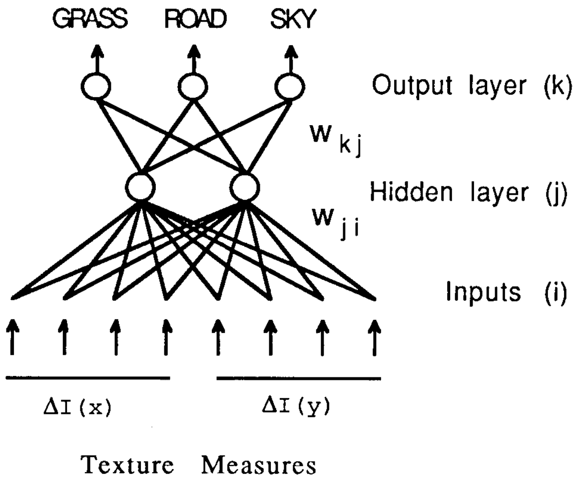

Fig.17 Structure of Multilayer Perceptron used for Texture Classification.

Instead of a single multi-layer structure, the network was composed of two blocks: one controlling the steering and the other regulating the speed and deciding when the vehicle should change lanes (Fig.18). The first block received information about the position and speed of the robot vehicle relative to other cars in its vicinity. Its output was used to determine the vehicle's speed and whether the robot should change lanes. The passing signal was converted to a lane assignment based on the car's current lane position. The second block received the lane assignment and data pertinent to the position and orientation of the vehicle with respect to the road. The output was used to determine the steering angle of the robot car. The two blocks were trained separately. This was found to be very effective because each block had a restricted, well-defined set of tasks, and the trainer could concentrate specifically on those functions without being concerned that other aspects of the network behaviour might be deteriorating. The system was trained from bottom up, first teaching the network to stay on the road, negotiate curves, change lanes, and how to return if the vehicle strayed off the highway! Block 2, responsible for steering, learned these skills in a few minutes using the master/apprentice or supervised training mode in which the trainer actuates the vehicle and the network takes the trainer's actions as the desired system responses and correlates these with the input. The ANN tended to steer more slowly than a human but further training progressively improved its responsiveness. After Block 2 was trained, steering control was handed to the ANN in order to concentrate on teaching the network to change lanes and adjust speed. Speed control in this case was a continuous variable and was best taught using master/apprentice training. On the other hand, the binary decision to change lanes was best taught by coaching. In this case the ANN remained in direct control of the robot vehicle, but the human trainer instructed it when and when not to change lanes. The network quickly correlated its environmental inputs with the teacher's instructions and after only ten minutes of training, the network became adept at changing lanes and weaving through traffic. It was found that the network readily adapted to the behavioural pattern of its trainer. A conservative trainer generated a network that hardly ever passed other cars, whilst an aggressive trainer produced a network that drove recklessly and tended to cut off other cars. This example demonstrated the ability of an artificial neural system to operate satisfactorily in an environment where the rule set governing an expert's decisions is difficult to formulate. Also imitations of expert behaviour tended to emerge as a natural consequence of their training.

Neural Network for Autonomous Navigation. We have seen that an Artificial Neural Network (ANN) can be used to control a vehicle successfully when presented with a limited range of discrete input parameters. This approach can be extended by presenting the ANN with a pre-processed image derived from a video sensor viewing the scene ahead of the vehicle and, with suitable training, conditioning the output to provide steering commands for the vehicle so that it drives safely along the desired route. A system known as ALVINN (Autonomous Land Vehicle in a Neural Network) has been designed at Carnegie Mellon University to drive the Navlab, their autonomous navigation test vehicle in this way. (Ref.29). The ALVINN architecture is of the Multilayer Perceptron form (Fig.19) with a single hidden layer back-propagation (supervised) network. The input layer of the network consists of a "retina" having 30 x 32 units on to which the video camera image is projected after preprocessing. The output array is a vector, typically 30 elements, in which each element represents the strength of votes for a particular steering direction. The middle layer consists of four hidden units. Each hidden unit is connected to all 960 inputs and to all 30 outputs. The system therefore contains 3960 total weights, 3840 connecting the input to the hidden units and 120 connecting the hidden units to the output units. These weights describe the representation of the road, and consequently the processing the neural net has to perform to generate the steering commands from the road images. ALVINN is trained by watching a human drive, using the video images as model input and human steering direction as desired output. The training process sets the weights for the interconnections. In a few minutes of training, ALVINN learnt how to drive on a particular type of road.

The colour input images are pre-processed to produce a single-band output image. Each pixel in the image is normalised to have a value between 0 and 1. The normalised value is given by:

$$\left[\frac{\alpha B}{255}\right] + \left[\frac{(1-\alpha)B}{R+G+B}\right]$$

where R, G and B are the raw red, green and blue values for a particular pixel; α is a weighting factor. This normalisation provides some tolerance to lighting variation. While the R, G and B values will change from sunlit to shadowed areas, the ratios of the values will stay approximately the same. Empirically, the blue band contains the most useful contrast for road following.

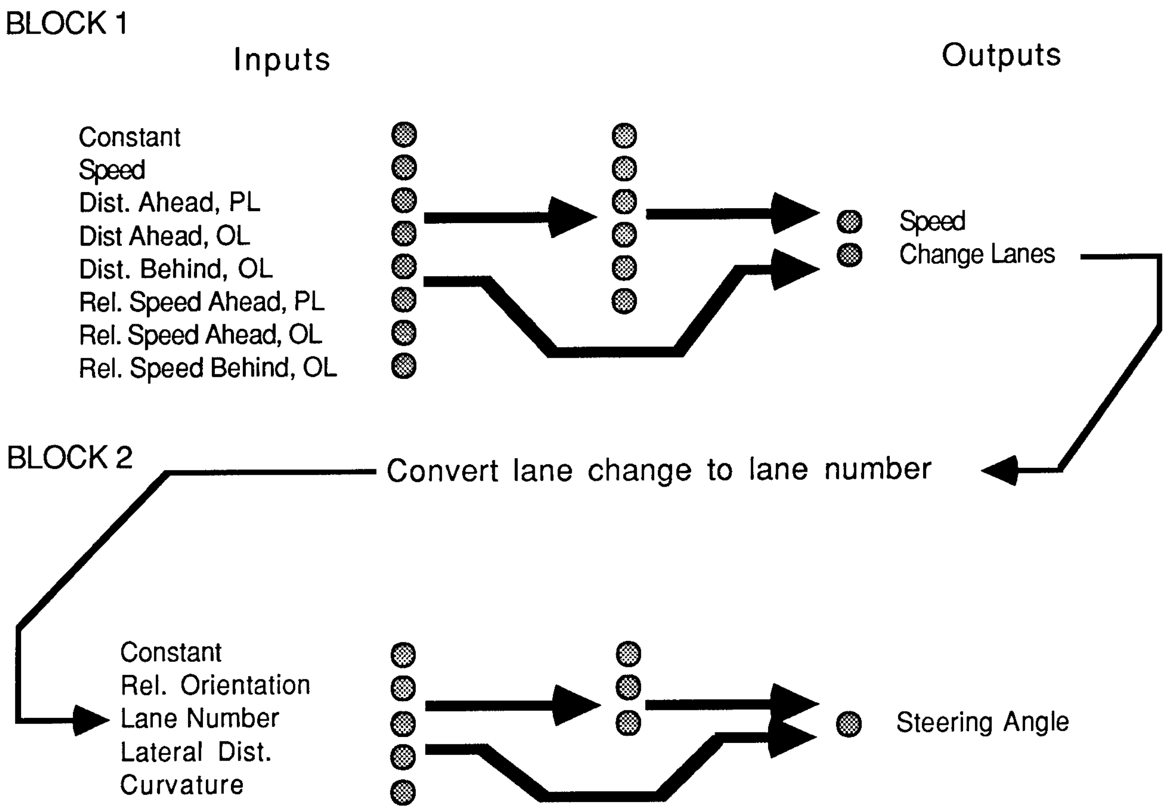

Fig.18 The two blocks of the driving neural network. Heavy arrows indicate total interconnectivity between layers. PL designates the traffic lane presently occupied by the robot vehicle, OL refers to the other lane, curvature refers to road, the lane number is either 0 or 1, relative orientation and lateral distance refer to the robot car's direction and position relative to the road's direction and centre line, respectively.

Of the video images, digitised to 480 rows by 512 columns, some 10% of the pixels are sampled and averaged to feed the input layer. This preserves some of the essential variability of the underlying image, whilst providing adequate smoothing in reducing the image size. The desired output is a steering direction. The actual representation used by ALVINN is a vector of outputs. Each element of the output vector collects votes from the hidden units for or against the steering direction which it represents. By fitting a Gaussian to the area around the peak activation (most positive votes) or by finding the centre of mass of votes in the neighbourhood of the peak, a continuously varying, well behaved steering output direction was obtained.

Back Propagation Learning. The training phase generated the weights connecting input to hidden units, and hidden units to the output. Back propagation learning was used in which the weights were initially set to random values. At each step of training, the system was run forward, from input pixels to output steering directions. The reported output was compared with the desired output. Errors in the output were used to adjust the weights that led to those output units. The process was run recursively at the hidden units, propagating the errors (and the corrections) back to the inputs. Back propagation was continued until the errors were acceptably low. Several subtleties arose in generating the training images used in learning. If the only images used came from a human performing perfectly at driving, ALVINN would never learn how to recover from minor steering errors. This was solved by creating derived training images from the actual images. Starting with a given input image and desired steering direction, the image was shifted or rotated slightly to create the image that the vehicle would see if it were slightly off the desired path. The desired steering angle was corrected correspondingly. This gave ALVINN a much broader training set aimed at encompassing the range of likely experience. Another subtlety involved the need to avoid bias: if the training used images only from left turns, ALVINN would learn that always turning left minimised output errors. The results obtained with ALVINN have been impressive, the vehicle being driven recently for 145km at speeds up to 113kph. However, the performance is still inadequate for realistic applications, and sufficient levels of generality, reliability and self diagnosis have not been achieved which would allow the vehicle to run unattended in a wide variety of situations. The approach adopted is very ambitious with the relatively simple neural network being tasked with both image understanding and constructive controller response. In fact, current research is now being directed at understanding more fully the behaviour of the inherent ALVINN system. For instance, how much does the design of the neural network

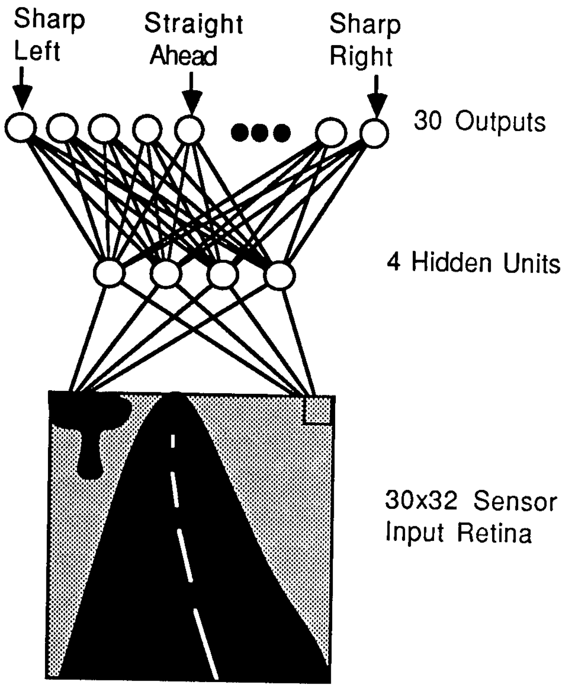

Fig.19 Neural network architecture for autonomous driving.

contribute to the performance by comparison with the training set generation or the output representation?

Having described both fuzzy logic control and artificial neural networks, we can see that they have some striking similarities. They both attempt to deal with real-time adaptive operation of complex linear and non-linear systems. In particular, a class of neural systems known as Associative Memory Neural Networks resembles fuzzy models under certain conditions. These have the advantage over the more popular Multilayer Perceptron (MLP) that they enable a satisfactory system performance to be obtained over widely differing sets of situations.

12.5 Road Detection Systems

We have seen how the UGV can be controlled in a predictable way when provided with reliable steering input information. This information has to be derived from some sensing of the local surroundings. In the case of cross country navigation, this becomes a task of detecting obstacles and discriminating gradients that the vehicle can negotiate. But, as with manned vehicles, the majority of driving will be on prepared roads or at least on unprepared surfaces where there are some delineating features which determine the trackway. The problem of autonomous navigation can only be solved, therefore, if a reliable system of automatic road detection can be developed.

In principle, there are two stages to the problem. Firstly, there is the recognition of the road in question from some off road viewpoint, which will allow subsequent access to the road and, secondly, when access has been gained, there is the need continuously to identify the road surface to enable the vehicle to stay on the road. The first stage is an example of the general problem of scene or image understanding, whilst the second is somewhat easier, in that image comparisons of more distant views can be made with the immediate foreground, on the reasonable assumption that the road surface appearance will not change dramatically in the vicinity of the vehicle. This second stage must also allow continuous monitoring of the road boundaries and the differentiation between intersecting roads at junctions. Here we discuss some of the methods for discriminating roads in the global surroundings. We have already described systems which do not explicitly identify roads from an analysis of their physical properties. ALVINN, for instance, is trained on image data derived from a range of road scenes. We shall concentrate now on explicit techniques for road detection and this implies identifying those features of a road embedded scene which allow the road to be separated from its surroundings. Broadly the features are edge or region based.

Edge Techniques The edge features can be enhanced by the application of a convolution operator, e.g. Sobel operator, to the digitised video image. This should enable the road boundaries and road markings to be highlighted, and confirmation of the road edges obtained by comparison with a stored model of a representative road. The system adopted by Dickmanns (Ref.12) used a limited number of localised edge trackers to track the road edges. This allowed rapid computation at frame rates, and enabled the VaMoRs vehicle to achieve runs at up to 96 kph. Whilst the technique correctly focused attention on the road edges themselves, and gained some stability by being model-based, the trackers could be seduced by spurious edges arising from shadows and changes in road structure such as intersections. A more sophisticated approach (Ref.16) illustrated the processes involved in producing a more robust solution to the problem. The camera image is transformed into a plan view image which has the advantage that edge detection can be simplified to a vertical edge detector. There is, then, a sequence of operations which involves searching for edge segments, linking the edge segments, fitting road edge candidates into straight lines, selecting a pair of straight lines (the right boundary and the left), extending the lines with relevant linked segments, to overcome the problem of interrupted edges, and fitting the lines with two second-order polynomials to obtain the road curvature. Processing this sequence of operations was accomplished at a rate of 6 frames/sec.

Area Techniques Area or region based techniques rely on the characteristics of the road surface area being distinguishable from the roadside verges. Texture, gray level, and colour measures can be used as discriminants. All suffer from the inability to deal with widely variable characteristics of real road surfaces. Gray level sensing, for instance, depends on accumulating histogram data over the video scene image, and setting a threshold to differentiate the road from verge. The imaged road surface intensity level will depend on surface reflectivity, the sun direction, the degree of shadowing, and the nature of the verge surface, all of which will cause the optimum threshold for road discrimination to change. Colour adds an extra dimension to feature

measurement, and an adaptive colour classification system SCARF (Supervised classification applied to road following) has been developed by CMU (Ref.17) to avoid some of the shortcomings of the monochrome techniques. SCARF typically uses four colour classes to describe road appearance, and four to describe off road objects. In addition, the multiple colour classes are represented as Gaussian distributions in full red-green-blue colour, so that the probability of a pixel being assigned to a particular class can be determined instead of using binary thresholds. Multiple classes let SCARF represent the different colours of the road (such as asphalt, wet patches, shadowed pavement, and leaves) and off road objects (such as trees, sunlit grass, shaded grass, and leaves). Classified pixels vote for all road locations that would contain them with votes weighted by classification confidence. The road with the most votes is used both for steering and for recalculating the colour classes using nearest-mean clustering to collect new road and off-road colour characteristics. SCARF's simple model of road geometry represents roads as triangles in the image. The apex is constrained to lie on a particular row (the horizon) and the base has a fixed width, dependent on the road width and the camera calibration. There are two free parameters: the column in which the apex appears and the skew of the triangle. While this simple two-parameter model does not represent curves, hills, or road width variations, it does approximate the road shape well enough to allow reliable driving. It is especially effective because the voting procedure uses all pixels, not just those on the edges, and therefore is relatively insensitive to misclassifications. Furthermore, the simple model allows for fast voting, and highly reduced images (typically 60 x 64 or 30 x 32 pixels) can be processed at high sampling rates (approximately 2 seconds per frame). This enables small errors in road representations to be corrected before the vehicle arrives at the mistaken locations. Even drastic illumination changes caused by clouds covering the sun are perceived as gradual shifts in road appearance. SCARF has driven the Navlab on various roads: bicycle paths, dirt roads, gravel roads and suburban streets. The system has been extended by including in the road model the admissibility of intersections.

The road recognition task is also suited to the application of an artificial neural network (Ref.18). A Multilayer Perceptron (Fig.17) has been designed to operate as a texture classifier capable of distinguishing between three possible candidates, namely "road", "verge" and "sky". The texture measures used were the standard deviation of differences in intensities ΔI between pairs of pixels at 1, 2, 4 and 8 pixel separations Δx, which can be simply and rapidly computed. Fractal textures are characterised by a linear plot of log ΔI against log Δx, with rougher textures having a steeper gradient. There is sufficient difference between the characteristic for the 3 candidate classes to make classification effective. The MLP, with 8 texture measures (4 horizontal and 4 vertical) as input and one hidden layer with 2 nodes, was trained on a range of country road scenes and achieved successful road classification on scenes taken from different geographical areas. Real time operation was achieved using a network implemented with transputers.

12.6 Mission Planning

An essential part of the tasking of an autonomous UGV is to define the route to the final goal or destination. This may be via a network of roads or tracks or across country. Typically a map at a scale of 1:50,000 can be used to create a network of nodes and route segments from which an optimum route can be planned. This optimum route may be chosen on the basis of minimum distance, minimum travelling time, or any other "cost" parameter. This so called A* algorithm is one of a number of route optimisation techniques which can be applied either before the mission commences or on-line during the course of the mission. The A* algorithm takes the "cost" (or optimising parameter) accumulated in reaching a given node from the start node, together with an estimate of the distance remaining to the goal node, to guide the search process for selecting the next node to be aimed for. Having chosen the overall route to the goal destination, various key waypoints, intersections and other landmarks can be selected and used as the necessary a priori information for "updating" the vehicle position in global co-ordinates when the vehicle sensing system identifies them en route. A route planner designed to support a wide variety of digital terrain databases has been developed by JPL (Ref.19). This route planner generates a 3D composite cost surface for the map area. It consists of a rectangular grid of nodes with each node of the surface corresponding to a point on the ground whose "height" (i.e. cost) may depend on various attributes. These may include, for example, elevation of the point, steepness of gradients, presence of water, marsh, or enemy threat. The relative influence of these factors on the cost is defined by the human mission planner. The composite cost surface is constructed for the geographic region under consideration, and the route planner attempts automatically to find the minimum cost path between start and end points using the nodes of the composite cost surface. The A* algorithm is used to generate the minimum cost path. Particular features can be avoided by associating a high cost with those nodes where the feature exists. In general, nodes associated with roads can be expected to merit low cost, but as the planner is free to explore routes via any of the available nodes in the composite surface, this approach will allow cross country routes to be proposed if these prove more favourable.

12.7 Route Planning

We refer to route planning as the local path planning which needs to be carried out by the autonomous vehicle in its attempt to execute the mission plan. It is an essential part of the sense-plan-drive cycle which governs the motion of the UGV. Three constraints can be defined which are important for enabling a safe trajectory to be planned in order to reach the goal, namely sensing, environmental and kinematic. Firstly, positions have to be selected where the UGV has to take some action, such as registering its position relative to the world in relation to landmarks, or acquiring new sensor data for identifying likely obstacles or characteristic features. These positions are intermediate goals that give the planner additional constraints. Secondly, there are environmental constraints which will

present obstacles to the UGV or prevent it from moving. Such situations will include steep gradients, upstanding obstacles, and holes in the ground. The identification of such environmental features is an essential and important task for the sensing system. Thirdly, there are kinematic constraints. UGV's are not omnidirectional and their manoeuvrability will be determined by their speed and steering characteristics. Again, the sensing system must provide sufficient warning in time and distance to allow for these limitations. In addition to these three basic constraints, an allowance must be made for uncertainty in the UGV's position. Sources of uncertainty range from random errors in the control system to gross errors such as wheel slippage. The local path planner must take into account control based uncertainty to avoid collisions by allowing for an adequate "miss" distance in the planned trajectory.

The requirement for local path planning emphasises the need for 3D sensing of the local environment, ideally out to the limit of the visible horizon. In practice, as we shall see later, this will be determined by the range capability of the on board sensing system. A 3D representation of the scene ahead of the vehicle will allow the local path planner to choose the "best" route (minimum gradients and avoiding obstacles) in the direction of an intermediate or ultimate goal. An updated 3D representation obtained at a later time when the vehicle has advanced along the planned route will enable a revision to be made to the route, and so optimise the next stage of the route to the goal.

12.8 3D Mapping

We have seen that 3D mapping is necessary both for route planning, and to allow for the kinematics of the vehicle in order to give sufficient advanced warning of features which require the vehicle to react. The most direct means of generating a 3D map is to design a high repetition rate rangefinder system which can scan an adequate field of view in a frame time which is compatible with the response time of the vehicle. This implies a repetition rate of many tens of kilohertz, a wide angle scanning system (typically 30° x 20°) and a processing system which can construct the map from the 3D information. Taken together, this constitutes a formidable requirement, but systems have been built at considerable cost and complexity which have provided the primary sensing facility in this way. An alternative approach is to provide a simpler rangefinding system which can be used to complement the 2D imaging system which is so conveniently obtained from a TV camera. The rangefinding system in this case would assist in resolving ambiguities in the 2D scene, such as confirming or otherwise the existence of physical discontinuities indicated by spurious edge boundaries on the 2D image. The coupling of data from two disparate sensor sources introduces a new topic for study, namely data fusion, and this will be discussed later.

We shall now describe some of the characteristics of the various rangefinding systems which have been used in mobile robotics. These fall into two categories: active and passive. Active systems involve the transmission and reception of pulses of energy reflected from the object field such as ultrasonic, laser, and millimetre wave radar. Passive systems involve the processing of data from stereoscopic imaging sensors or optical flow sensing.

Ultrasonic Sensors Such sensors are attractive for robotic applications because of their low cost. A typical device is that manufactured by Polaroid as a camera rangefinder. The range is measured in terms of the time of flight of a burst of ultrasound. The resolution of such a system is limited by the wavelength of the radiation used; at 50kHz this is about 6mm. This in itself implies that surfaces whose roughness is less than this dimension will tend to appear specular and hence targets may not be detected if the specular return does not fall within the reception angle of the receiver. The simplest detection system uses basic thresholding, with time varying gain to allow for the decrease in received signal at greater target distances due both to dispersion of the echo after reflection and attenuation of ultrasound in air. This leads to maximum detection ranges of 10m for discrete objects, and considerably less for objects in cluttered backgrounds. The effective beam width of the Polaroid transducer is about 30° which implies that the accurate bearing of objects cannot be obtained by this system. The receiver can be baffled to reduce its angular reception angle by up to 50%, but this also reduces the range sensitivity and increases the sensitivity to orientation effects of the target. To measure the angular position of a target, it is necessary either to rotate the beam mechanically or to use more than one transducer. Phased arrays are used in radar and these enable beam steering to be done by varying the phase at each element in the array; this can be done either in transmission or in receive mode. The angular resolution of such a system is maximised by making the separation of the array elements as large as possible; however, side lobes are obtained unless the minimum separation is of the order of half a wavelength (3mm at 50kHz). An eight element array receiver with half wavelength separation has been built (Ref.20) giving a bearing range of 60° and a resolution of 6°. Subsequently it has been found possible to use the envelopes of the bursts of ultrasound instead of using the phase to measure the time delay. This eliminates the problem of side lobes and has enabled four element receivers to be used with relatively large inter-element spacing (15 wavelengths) giving good angular resolution and requiring considerably less hardware and processing than the half wavelength system. Present designs allow beam steering in one direction only and maximum sensitivity to targets aligned at right angles to this direction. Research is currently aimed at removing these restrictions.

In summary, ultrasonic rangefinders seem best suited as short range obstacle warning devices, a fixed array of contiguous rangefinders giving "bump bar" protection at ranges of 1 -3 m. They are capable of accurate range measurement, as we have seen, but their wide beam width makes them sensitive to spurious reflections, whilst re-entrant surfaces can suppress reflections and inclined targets can deflect reflections outside the receiver beam angle, rendering their performance somewhat unreliable. They will be less affected by smoke, dust and ambient light levels than optical systems, but their performance may well be degraded by rain or mud or interference due to noise and vibration.

Laser Rangefinders The characteristic feature of the laser is its narrow beamwidth and this offers the possibility of good angular discrimination in the object field. However, this brings with it the need for accurate synchronisation with the scanning system which has to be capable of covering a wide angular field in two directions in one second or less. Range is determined by measuring the time of flight between the transmitted beam and the received radiation after reflection from the target surface. Three different techniques can be employed to measure the time of flight (1) Pulse detection which measures the time of flight of discrete pulses, (2) Coherent detection which measures the time of flight indirectly by measuring the beat frequency of a frequency-modulated continuous wave (fm-cw) emitted beam and its reflection, and (3) Direct detection, which measures the time of flight indirectly by measuring the shift in phase between an amplitude-modulated continuous wave (am-cw) emitted beam and its reflection. Experimental systems using all three techniques have been built, but most systems developed as imaging laser radars have been based on pulse detection or am-cw. For both such systems the GaAs semi-conductor laser operating in the near infra-red wave band (800-900 nanometres) is capable of modulation at repetition rates of typically 25kHz. Peak pulse powers of 10watts for pulse detection and mean output powers in the range 100-300mw for am-cw have been reported (Refs.21,22). In the pulse detection system (Ref.21) the rangefinder was scanned in a raster over a 40^ox30^o field of view by two rotating coaxial polygons. The laser was fired in synchronism with the scan and measured the range to points in the scene at equal angular intervals of approximately 0.5^o, giving a 56x55 pixel display. The range resolution was 2.5cm (s.d.) measured against a normal target in the measurement range 6m to 50m. The sequence of operations applied to the raw range data was as follows:-

(1) Scan conversion; a look up table reordered the pixel data obtained from the scanner.

(2) The slope (relative to the vertical) of each triangular elemental area defined by 3 neighbouring pixels was determined.

(3) Region growing was carried out to associate clusters of elemental areas with slopes greater than a critical value (defining an obstacle for the vehicle in question). Neighbouring areas were clustered if their range separation was less than a preset value.

(4) A simple obstacle description was obtained by enclosing the obstacle clusters in boxes.

(5) The pathlength to the nearest box-obstacle along a given bearing from the sensor was supplied to the navigation subsystem.

The system demonstrated the principle of detecting upstanding obstacles in the path of the vehicle, but two problems became evident as a result of this work. In order to achieve a useful maximum range from the system, the collecting area of the receiver needed to be several square centimetres. With the scanner mechanism operating in the object field, this implied that the scanning system of rotating polygons was both large and heavy ($30x30x30cm^3$). Alternative oscillating plane mirror systems can be equally cumbersome (Ref.22). Secondly, the pixel points in the image were scanned by the polygon system in a fixed but random sequence. When the vehicle platform was in motion this led to "image smear" due to the processing of adjacent pixels whose data was gathered at different time intervals.

We can conclude, therefore, that laser techniques can produce accurate and precise directional range image data out to ranges of 50m depending on target reflectivity. Mechanical scanning techniques enable wide angle fields of view to be scanned, but the design of wide angle two dimensional scanning systems suitable for operation on vehicles in field environments is not a trivial problem.

Millimetre Wave Ranging. Millimetre wave techniques do not suffer many of the environmental difficulties which beset ultrasonic and laser ranging such as smoke, fog and mud. However, with frequencies in the GHz band, problems centre on beamwidth, accuracy of ranging and ability to range effectively on non-metallic objects as well as metallic objects due to relative absorption. The technique is ideally suited to detecting and tracking vehicles ahead of the vehicle having the installed radar, because the large radar cross section of metallic vehicles ($10\text{-}15m^2$ at 94GHz) can ensure strong returns from distances well beyond 300m. However, for the route finding and navigation task ranging to natural objects is required and, as these are mostly non-metallic, detection is much more problematic, with radar cross-sections for miscellaneous road debris being typically $0.1m^2$. By comparison, the cross-section of a road surface is $<10^{-4}m^2$ per square metre of road area which is sufficiently low to offer the possibility of detecting debris lying on a prepared road surface (Ref.23)

Modern solid state technology has solved the problem of the generation of power at millimetre frequencies, the maximum power for human safety of 10mw being easily generated by a solid-state Gunn diode oscillator at 80GHz. The easiest modulation required to obtain range resolution from a cw source is frequency modulated continuous wave (fm-cw). The transmitter frequency is varied linearly with time at a "chirp" rate α (Fig.20), and the transmitted and received frequencies are mixed together in the receiver mixer to generate a constant beat frequency. If the time delay from transmission to reception is τ and the rate of change of transmitter frequency with time is α, then the beat frequency f_b will be $f_b=\alpha\tau$ (Fig.20). If the range is r, then $\tau=2r/c$ where c is the speed of propagation. The beat frequency is thus $f_b = 2\alpha r/c$ so the range to the target can be found by measuring the beat frequency. It can be shown that the range resolution is dependent on the bandwidth over which transmission occurs and, for car obstacle avoidance radars, this will typically be about 150MHz to give a range resolution of 1m with a period of about 1ms. The beat frequency from a target at a range of 250m will be 250kHz. If this is the maximum range of interest then the receiver's IF bandwidth will be between 1kHz and 250kHz. The processing is ideally suited to the use of a digital signal processor (DSP) chip to perform a fast Fourier transform (FFT) on the IF signal.

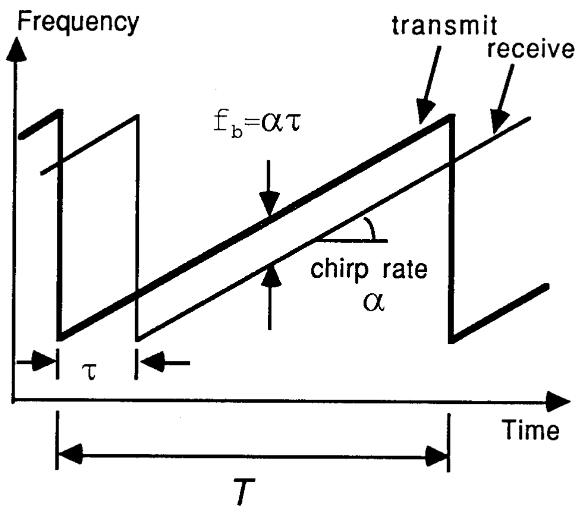

Fig.20 Principle of FMCW radar

There remains the question of receiver dimensions. This will be dependent on the transmitter wavelength and the beam divergence required. At a frequency of 80GHz (wavelength 4mm) the approximate antenna width for a 1 degree beamwidth is 25cm which is still quite large for a convenient installation. Scanning presents a further mechanical problem but, of course, the need for this can be sacrificed at the expense of a wider beamwidth.

In summary then, modern technology is now bringing nearer the feasibility of millimetre wave radar for cost effective obstacle detection, and intelligent cruise control with which a vehicle can maintain a safe distance behind the vehicle in front on the open highway. However, it is not clear at present whether such systems can assist the navigation of UGV's in the cross country environment.

3D Mapping by Passive Vision Shape can be perceived by comparing the images of a scene observed from different perspectives. This is most obviously implemented by using binocular stereo, depth being deduced by triangulating over the stereo baseline. Practical constraints tend to limit the length of the base line and hence the accuracy of depth measurement. Maintaining correct registration, and stable calibration, are other problems which have to be faced. On the other hand, it is also possible to make use of object or sensor motion to obtain multiple views with a potentially longer base line for triangulation. This can be done by capturing sequences of images from a single moving camera and generating structure from motion by appropriate processing. This is the basis of the DROID system developed at Roke Manor Research Ltd. (Ref.24). The concept depends on identifying features or tokens in a video frame and tracking the corresponding features in subsequent frames. It is important to avoid ambiguity in matching the features between frames, by locating the features reliably and as precisely as possible. This is carried out by a corner detector algorithm which locates vertices of objects and spots which occur in the images of the viewed scene. Typically up to 400 corners are detected within a single 256x256 pixel image. Determination of the correspondence of the current frame with the emerging 3D representation through feature matching, enables the camera motion estimate to be refined. This is important since it is a knowledge of the camera motion between frames which determines the ultimate accuracy of the range distance data. The 3D representation of the surface structure is developed using Delaunay triangulation. This allows a compact set of triangular facets to be generated in the image plane using the set of the most reliable 3D points, each triangular facet being single valued in depth from the camera. This representation is then used to construct a set of surface contours, typically 1m apart parallel to the road and with transverse contours at a spacing of 3m. Finally, the contour map is segmented into regions which are traversable for the vehicle and those which are not traversable. In practice, the addition of a second "stereo" camera improves the accuracy of measurement of the camera ego motion as well as providing some 3D information when the vehicle platform is stationary. This technique involves a heavy computational load, but real time operation is now becoming feasible and should allow the potential to be realised in practice.

Whilst the DROID technique offers a powerful passive means of generating a 3D representation of a static scene, there remains the problem of detecting and tracking moving objects in the field of view. A recent development uses optical flow measurement to distinguish object movement relative to the surroundings as seen from a moving platform (Ref.25). The system is termed ASSET (A Scene Segmenter Establishing Tracking) and again depends on feature based matching between frames in the image plane. This is then followed by object segmentation and tracking. Each frame taken by the video camera is initially processed to find two dimensional features and edges. This is a key factor in the process and, in order to match features between frames, both image brightness and local image spatial derivatives are used. These image functions are combined into a vector which is compared with the corresponding vector in the second image. The flow vectors are next segmented into regions which have consistent internal flow and which are different from each other. This makes the reasonable assumption that the separately moving image regions have "roughly constant" image flow which is different from the flow of adjacent regions. Having clustered the image flow vectors, the outline of each cluster is found using the outlying feature points of the cluster. If overlap is found, the cluster which will be occluded is predicted using the safe assumption for ground based situations that this cluster will have a higher image position for its lowest point than will the other cluster. Fine tuning of the cluster boundaries is then carried out using edges from the original image. The ASSET technique has proved successful in dealing with scenes involving the viewing of overtaking vehicles from a following vehicle. It requires no camera calibration or knowledge of the camera motion. The next stage is the integration of ASSET with the structure-from-motion system which recovers world structure in a static environment. ASSET will be used to segment out and track moving vehicles, and the static part of the scene will then be tracked by the structure-from-motion system.

12.9 Data Fusion

In order for a mission to be completed successfully the correctness of decision making en route must be of a very high order. This is particularly necessary in the case of route finding and obstacle detection and, as we have seen, no one technique will provide the ultimate solution to the problem. Several possible sources of information are available in the form of sensor data, digital map data or other forms of prior knowledge. The UGV control system has been considered to be made up of a number of processing levels (Fig.9). The lowest levels process the raw sensor data to extract information, whilst the higher levels attempt to reason with the extracted information in a more symbolic manner. Data fusion can be considered within or bridging these levels by aggregation of information and representation at a higher level. A specific example is the case of low level data processing for UGV guidance along a road. The raw data will comprise colour television images and the requirement is reliably to determine the road location. The images can be processed to extract candidate road surface using colour, texture and 3D processing. None of these techniques will be totally reliable on their own, but data fusion applied in an effective way should improve the situation.

There are several possible approaches including statistical inference, fuzzy logic, rule-based systems, Kalman estimation, neural networks and others (Ref.26). Statistical inference methods allow the combination of information if the appropriate probabilities can be obtained, for example by training. A tree of hypotheses is set up concerning the label (e.g. road, verge, sky, other) which should be attached to each picture element in the sensor image. Each image processing module then delivers evidence, for example, in the form of a probability, which is appropriate to some level in the tree, and which concerns the label to be attached to the picture element. The probabilities can be combined according to Bayes' rule to remain consistent across the label tree, and the combined probabilities are used to decide on the most appropriate labelling of the image.

To illustrate how Bayes' decision theory can be applied to fuse information, consider a simple case where there is assumed to be complete statistical knowledge of the process. It is required to determine $P(s_j|X)$ which is the conditional probability that the labelling (state of a nature) at a pixel site is s_j given a set of measured features $X=\{x_1,x_2,\ldots,x_n\}$

Direct determination of the probability $P(s_j|X)$ does not accord well with human experience and may be ill-defined because of noise, or otherwise ill-conditioned. However, Bayes' rule may be used to split $P(s_j|X)$ into two parts which depend on the available measurements and prior knowledge of the labelling. Thus,

$$P(s_j|X) = \frac{P(X|s_j)P(s_j)}{P(X)}$$

where $P(X|s_j)$ = probability of a measured feature X given that the label is s_j.

$P(s_j)$ = prior probability that the label is s_j

$P(X)=\sum_j P(X|s_j)P(s_j)$

If the $P(X|s_j)$ are known or can be estimated from training data, then they may be combined with prior knowledge, or an estimate of $P(s_j)$ to provide a maximum a- posteriori estimate of s_j. This form of approach has been applied to processing colour images for autonomous vehicle guidance (Ref.27). Here the states of nature comprised "road" and "non-road" and the feature vector consisted of 6 colour components from two colour cameras. A number of Gaussian models were assumed for the colour of road and non-road areas, and the parameters of their class conditional densities $P(X|s_j)$ were initially determined by supervised learning and then iteratively updated. $P(s_j)$ was estimated as the ratio of the number of pixels in s_j to the total number of image pixels.

13. COMPUTING TECHNOLOGY

Much of the low level processing that has been described is very computationally intensive, and the quest for real time operation focuses the attention on the development of computing power which will realise this in practice. In order to obtain a benchmark for the computing power needed, we can consider a basic convolution operation on a frame of video data. For an n x n convolution over an image of N x M pixels the number of operations P per sec at a frame rate of f/sec is given by $P=n^2NMf$.

Substituting typical values of n=5, N=M=512 and f=25 we obtain $P=164\times10^6$ operations per second or 164 Mops. We have seen that 3D mapping, using DROID for instance, involves a sequence of processes, namely (1) corner detection, (2) corner matching, (3) 3D calculation, (4) contour fitting. This is followed by higher level reasoning about the traversability of the contour map. Thus at least 5 levels of processing are required before control instructions can be issued to the vehicle controller. Of course, the higher levels of processing will be operating at lower effective frame rates (vehicle response time typically 10Hz or less) and smaller units of data than the pixel level will then be involved but, nevertheless, operations at 1000 Mops per video frame can be envisaged as a commonplace requirement. Fortunately, much of the lower level processing is well suited to parallel operations which matches well to modern computer architectures.

The development of microprocessor chips has led to computing power being doubled every two years over the period 1985 to 1993. Currently the Intel i860 vector processor operates at 80MFLOPS (Floating Point Operations per second) and the T9000 transputer at 25 MFLOPS. Of the Sun family of workstations, the SPARC 10 machine introduced in 1993 operates at 10 MFLOPS. The Intel 80586 microprocessor which appeared in 1993 uses a clock speed of 50MHz, and plans have been announced for a 2000MIPS (instructions per sec) microprocessor to be introduced in the year 2000 (the 80886?) operating with a clock speed of 250 MHz. This competition has led Motorola to leak plans for a 4000 MIPS reduced-instruction-set microprocessor as their state of the art, year-2000 microprocessor.

Parallel computers, typified by the WARP I machine which is in use on the Carnegie Mellon University Navlab vehicle testbed, first appeared in 1985 with a

capability of 80 MFLOPS. The WARP II then achieved 1200 MFLOPS in 1990.

By comparison, Symbolic Processors have seen a similar escalation in performance with time. Their computing speed is measured by the rate of logical inferences which they carry out per second (LIPS). A logical inference operation makes the deduction that "If A, then B". In 1988 a portable ruggedised LISP machine was operating at 10 MLIPS, whilst the Connection Machine with 65,000 processors was achieving nearly 1000 MLIPS.

In the area of dynamic random access memories (DRAMs), progress is expected to continue at the same rate as that realised over the past 25 years with DRAM chip densities quadrupling every 3 years. 64Mbit DRAMs were scheduled for sample introduction in 1993, 256 Mbit DRAMs are planned for 1996, and 1000 Mbit DRAMs should make their sample-quantity debut around the year 2000.

Thus there is no sign at present that the increasing availability of computing power is about to tail off and, therefore, significant advances in intelligent decision making for autonomous vehicles can be anticipated in the near future.

14. AUTONOMOUS GROUND VEHICLE TEST BEDS

Research on autonomous ground vehicles has led to the development of a number of vehicle test beds. Some are laboratory based, others project based. The VaMoRs vehicle at the Armed Forces University at Munich, ROVA at DRA Chertsey, DARDS at SAGEM in France, and the Navlab at Carnegie Mellon University are examples of laboratory based vehicles. The PANORAMA project, a part of the European Esprit Programme has also generated autonomous research vehicles, and another European initiative PROMETHEUS has done likewise. The PROMETHEUS project was started in 1986 and is jointly funded by Government and the European Motor Manufacturers. One of its objectives is to improve safety on the public highways of the future. To this end intelligent cruise control, collision avoidance and dual mode route guidance are research topics which impinge on autonomous navigation, and many of the collaborating nations have test vehicles to demonstrate their achievements in these research areas.

Two systems are now described in more detail as they provide examples of total vehicles embodying many of the subsystems and technologies which have been discussed earlier. The two projects are the PANORAMA ESPRIT II (Ref.28) and the Navlab (Ref. 29).

Panorama. The project aims to develop a perception and navigation system for autonomous outdoor mobile robots and is built around a 4 x 4 road vehicle. A hierarchical approach was chosen similar to the NASREM architecture (Fig.11) with the obstacle avoidance loop comprising a fully integrated system coupling higher levels (planner) with lower levels (data acquisition, actuation). The system has been tuned to work at low speed (<5m/sec) on relatively even terrain, but its generic design will allow extension to more demanding constraints. The sensor system is based on scanning rangefinders, ultrasonic for ranges up to 5m, and laser for ranges up to 50m. The laser beam scans at 1kHz in azimuth only, whilst on the move, and delivers measurements indicating free or occupied sectors. The environmental modelling produces a probabilistic occupancy grid having typically 128 x 128 cells each 50cm x 50cm. Updating from a single scan takes around 10 - 20 ms. The local path planner has the task of directing the vehicle on the planned route whilst avoiding unexpected but perceived obstacles. It provides continuously an updated trajectory for the piloting system computed with geometric and kinematic constraints. At the end of the obstacle avoidance loop is the Piloting System whose purpose is to follow the instructions of the local path planner. This employs a hierarchical architecture with four separate modules (1) a trajectory generator [a servo loop on trajectory and goal position at 0.1 - 0.5Hz] (2) a trajectory follower [a servo loop on position/orientation at 4Hz] (3) a kinematic controller [a servo loop on speed/heading at 20 Hz] and (4) a dynamic controller [a servo loop on throttle valve angle/brake pressure/steering angle at 100Hz].

The method of trajectory planning is goal driven so that the presence of obstacles does not systematically generate motion reactions, as all obstacles are not necessarily in the planned corridor. Therefore, fine piloting control is possible with smooth obstacle avoidance while moving. Also the environmental modelling by grid representation is generic enough to allow efficient fusion of information coming from a priori knowledge and sensors (lasers, ultrasonics, vision).

Carnegie Mellon Navlab. The Navlab is a testbed for research in outdoor navigation, image understanding and the role of human interaction with intelligent systems. The vehicle was first conceived in 1985 and is based on a General Motors van whose final all-up weight has reached 5.3tons. The length of the vehicle is 5.5m and the minimum turning radius 7.5m. The Navlab controller manages all locomotion. It interacts with a computer host and human operator to implement various degrees of autonomy. The controller queues and executes commands originating from a computer or human host, providing a "Virtual vehicle" interface that hides details of the actual hardware and therefore facilitates adaptation to future navigation testbeds. The control computer accepts commands from a host or human operator who can intervene at various levels of control to ensure safe operation during experiments. It was assumed that, during development, the higher levels of computing would not succeed in all situations. The control computing therefore provides a graceful transition between computer and human control when failures occur. The human input facility is also useful for set up and recovery during experiments. The sensing system provides for vision, laser and ultrasonic ranging. A fixed video camera system is mounted in the front of the vehicle above the driving cab and provides a wide angle view of the scene. The current laser ranging device, manufactured by ERIM, operates at a wavelength of 900 nanometres and produces a 256 x 64 x 8 bit depth map at 2 frames per second. Each sensor commonly requires its own workstation or specialised processor. Another computer runs the

blackboard system that integrates perception, modelling and planning.

The Navlab project seeks to build complete autonomous systems capable of outdoor navigation, both on roads and cross-country. The biggest challenge has been in the area of image understanding in difficult conditions with the emphasis on unstructured roads, on the changing appearance of structured roads in dappled shadows and at intersections, and on off-road navigation over rough terrain. The Navlab vehicle has driven autonomously at slow speeds along unmarked, unmapped trails, locating and traversing intersections. On more typical structured roads the vehicle has driven up to its mechanical limit of 28kph. It can run without a map or use maps it has built, along with information from previous runs, to select different behaviours at different locations. Off road the Navlab can move slowly over moderately rough terrain and can map large areas as it drives.

The current research programme is addressing two particular areas: machine learning and human-computer interaction (Ref.15). Machine learning is not directed at building new capabilities but at automatically improving the performance of existing systems. The work on human-computer interaction (HCI) is to fill gaps in the operating profile where the vehicle cannot reliably run autonomously. STRIPE has already been described (Section 11) and is an example of the HCI thrust on supervised teleoperation. ALVINN (Section 12.4) is an example of machine learning using neural nets.

More recently (Ref.15) machine learning has been used to improve a feature based trajectory vision system. This system is the YARF (Yet Another Road Follower) which has specialised trackers for finding yellow lines, white lines and other scene features. It finds the features in one image, updates its model of road location and shape, and predicts where the features should appear in the next image. The individual feature trackers are good but not perfect. There are several areas where machine learning could be used to improve YARF's performance of tracking white and yellow lines. The road follower Chameleon is being built to address two separate problems: the confidence problem and the location problem. The first experiment is to learn confidence measures for deciding whether lines are present in the predicted tracking windows. In the second experiment, the location estimation of the features is being tackled. In both cases a supervised neural network, trained by back propagation, is used. This should enable a better understanding of relatively well defined image features to be obtained, rather than attempting to solve the overall driving problem using a single artificial neural network as in ALVINN.

The Navlab will be embodying these techniques as they are proved. Already supervised teleoperation using STRIPE can be switched to autonomous driving during a run. Even while driving with STRIPE the automatic obstacle detection system can be kept running to provide a "soft bumper". This increases safety and robustness, while decreasing the operator workload.

The Navlab project is an excellent example of fundamental research being directed at the practical problems of autonomy, and demonstrating the results of this research on a fullscale test bed which has the potential for further extension of its capability for some years to come.

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Human Factors Considerations for Remote Manipulation

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SUMMARY

This paper presents human factors considerations of remote manipulation, sometimes called teleoperation. The paper reviews two broad classes of sensing and display considerations, namely (1) vision and video feedback, and (2) haptic sensing and display, including force and touch feedback from remote manipulators. Next "telepresence" and virtual environments are discussed in relation to one another. The paper then discusses two broad classes of teleoperator control, namely (1) direct manual control and (2) supervisory control. Finally the paper considers briefly the subjects of cognition and mental models as they relate to remote manipulation.

This material is drawn largely from reference [1], a recent book on teleoperation, automation and supervisory control by the author. Many sentences and paragraphs are direct quotes from that book, except for reference and figure numbers (hence quotes are not used). The organization of the material differs.

INTRODUCTION

Some Definitions of "Tele" Terms

The following are not the only terms which may be new to the reader not already familiar with the field; others will be introduced as needed. This set of definitions of "tele" terms, in modified form from reference [1], is presented here to emphasize the special human communication aspects of remote manipulation.

A *teleoperator* is a machine that extends a person's sensing and/or manipulating capability to a location remote from that person. A teleoperator typically includes: artificial sensors of the environment; artificial arms and hands or other devices to apply forces and perform mechanical work on the environment; a platform or vehicle for supporting or moving these in the remote environment; and communication channels to and from the human operator.

Telemanipulation is sometimes used as a synonym for teleoperation, unless one means remote control of a vehicle for inspection only.The term *teleoperation* refers most commonly to direct and continuous human control of the teleoperator, but can also be used generically (and literally — i.e.,"operating at a distance") to encompass *telerobotics* .

A *telerobot* is an advanced form of teleoperator which a human operator supervises, or on which he employs *supervisory control*.. That is, the operator intermittently communicates to a computer information about goals, constraints, plans, contingencies, assumptions, suggestions, and orders relative to a remote task, getting back integrated information about accomplishments, difficulties, and concerns and (as requested) raw sensory data. The subordinate telerobot executes the task on the basis of information received from the human operator plus its own artificial sensing and intelligence. The term *supervisory control* is commonly used to refer to human supervision of any semi-autonomous system (an aircraft, a chemical or power plant, etc.) regardless of the distance separating it from its human operator(s), while the term *telerobotics* commonly refers to supervisory control of a teleoperator (a machine that is remote from the operator).

An *anthropomorphic* teleoperator or telerobot has a human-like form, in that it senses its environment with what resemble eyes, manipulates mechanical objects with what resemble arms and hands, and/or moves in many directions with what resemble human body motions. Thus the anthropomorphic teleoperator or telerobot provides the human operator with an important remote body image, which the *non-anthropomorphic* teleoperator or telerobot does not.

Teleproprioception refers to the human operator's sensing and keeping track of the location and orientation of the teleoperator and its arms and hands relative to its base, to each other, to external objects, and to the location of the operator's body, arms, and hands. The closely associated term *telekinesthesis* refers to the operator's ability to identify the dynamic movements of the teleoperator and its arms and hands relative to its base, to each other, to external objects, and to the velocity or forces imposed by the operator's body, arms, and hands.

Telepresence refers to a person's experiencing a state of being present in an environment other than where the person actually is.

VISUAL SENSING AND DISPLAY

Comparison of direct vision vs. closed circuit video

The most important sensory communiction channel for remote manipulation is vision. For some teleoperation tasks which are not too distant, e.g., viewing radioactive objects through leaded glass windows, peering out through manned submersible portholes, viewing near space telemanipulations from within pressurized space vehicles, direct viewing is preferred over video. Whether or not this is wise depends upon how close the video camera can be brought to the objects of interest, whether the camera has pan, tilt, or translational capability, what are its contrast and illumination ranges and frame rate, how well it reproduces color, and how important any of these factors is for the job to be done.

Massimino and Sheridan [2] compared telemanipulation capability for direct vision vs. video in simple block-insertion tasks. They found that mean task-completion times dereased dramatically as the subtended angle of the critical objects in the visual field increased beyond 1° and the frame rate increased beyond 3 frames per second (Figure 1). However, for broadcast standard resolution there was no significant difference between direct viewing and video when the total visual field of objects to be manipulated was the same.

The importance of color is obviously task dependent, and may be overplayed. In this regard it is interesting to note that Murphy

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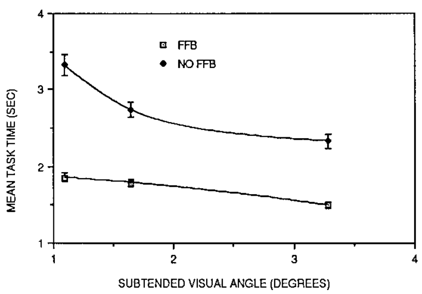
a)



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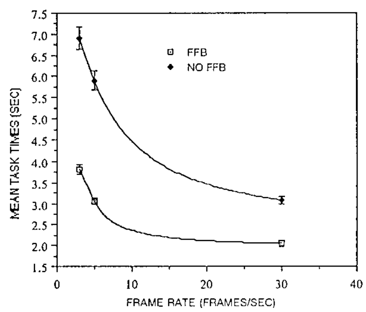

Figure 1. Massimino's results showing decreasing completion time of block insertion as (a) visual angle and (b) frame-rate increase. Force feedback and no force feedback conditions are compared. Bars indicate standard error of the mean. [From Massimino, ref. 2]

et al.[3] found that experienced dermatologists could diagnose skin lesions as well over black-and-white video as over color video.

The tradeoff among frame rate, resolution, and grayscale for bandlimited communication

When signal bandwidth is limited, as is often the case for deep space radio or underwater sound communication, it may be important to ask how best to trade off the three variables of frame rate (frames per second), resolution (pixels per frame), and grayscale (bits per pixel), the product of which is bandwidth (bits per second).

These tradeoffs were studied by Ranadive [4] in the context of master-slave manipulation. Experimental subjects were asked to perform two simple assembly tasks using a video display as their only feedback while using a seven-degree-of-freedom remote manipulator. The video display was systematically degraded with a special electronic device that allowed the frame rate to be adjusted to 28, 16, 8, or 4 frames per second, resolution to be adjusted to 128, 64, 32, or 16 pixels linear resolution, and grayscale to be adjusted to 4, 3, 2, or 1 bits per pixel (i.e., 16, 8, 4, or 2 levels of CRT intensity). The data-collection runs were ordered so that two of the three video variables were kept constant while the third was varied randomly among the levels for that variable.

Figure 2 shows the results. On the top row are shown the performance effects of frame rate, resolution, and grayscale while the other variables are held constant. Note that for frame rates beyond 16 frames per second improvement depends on resolution and grayscale; performance improves smoothly for increases in resolution; for grayscale there is no improvement beyond 2 bits if the frame rate is high enough. On the bottom row, constant-level-of-performance tradeoffs (in this case using the take-off-nut task only) are shown for each of the three pairs of video variables. These iso-performance curves (solid lines) are compared to iso-transmission lines, i.e., combinations of the two parameters which produce constant bits per second. It is seen that there is a remarkable correspondence. This means that, for this experiment, and within the range of video variables employed, human-and-machine performance corresponds roughly to bits per second of the display, regardless of the particular combination of frame rate, resolution, and grayscale.

If a limited-bandwidth channel must be used as the means for communication between human operators and teleoperators, it seems reasonable to allocate these fixed channels as required by the task at each moment. That is, frame rate, resolution, and grayscale would not each have fixed bandwidth allocations; rather, provision would be made to trade off among these as needed, keeping their product as close as possible to the maximum.
Deghuee [5] used an experimental computer-based aiding device which allowed the operator to make this three-way adjustment in situ, i.e., he could adjust the F-R-G tradeoff himself while performing a master-slave manipulation task of the type performed in Ranadive's experiments. As might be expected, by use of the tradeoff control performance was significantly better ($p < 0.05$).

Depth cues: stereo and other

Gaining a sense of depth is the most difficult visual problem when viewing through closed circuit video. To recreate the stereo sense of depth obtained when viewing a real object with two eyes, different 2D images must be obtained from two horizontally separated viewpoints, then presented to the corresponding left and right retinas. The brain recreates the 3D information from a variety of cues, of which binocular disparity is but one. In direct viewing, other strong 3D cues are accommodation, shadows, prior knowledge of relative size and of what object is behind what other object, and motion parallax (i.e., the ability to move the head from side to side and gain a different viewpoint). None of the latter cues requires two eyes. In televiewing accommodation is not available, and motion parallax is available only with head-mounted or other head-position-measuring display techniques).

For teleoperation the images can be obtained by two separate video cameras, or by a single camera outfitted with two optical paths sharing the video field in time or space, or by a geometric model run in a computer. Presentation of the images can be by means of two separate optical paths (one to each eye) or by a single display which provides two images in parallel. The latter can be separated for each eye by color filtering (wearing red and green glasses) or by temporal shuttering (alternate presentation to each eye of each corresponding image). Image transmission must maintain proper size, shape, brightness, and color (if color is displayed as such and not used for binocular channel separation). Many studies confirm a significant reduction in task performance time by use of stereo [6][7].

Stereopsis is not always practical; even when it is, depth perception continues to be a major reason why performance of direct manipulation is not matched by that of telemanipulation. Winey [8] evaluated three means to provide depth cues on a video or computer display: front plus side views (orthographic projection), artificially generated shadows projected on an imaginary horizontal floor, and an analog proximity indication of the distance between the gripper and the manipulated object. The operator's task was to operate a computer-simulated six-DOF manipulator so as to reach out and grasp a simulated sphere or block, which was stationary in some cases and moving in others. On both stationary and moving tasks, front and side orthographic projections showed the best performance. However, all the subjects felt the shadow gave them the best perception of the object's position in the environment. Winey suggested that the front and side views be combined with the shadow, where the shadow is used to provide an intuitive perception, while the side and front views provide the detail.

Stereopsis is not the only depth cue for video. Kim et al. [9] showed that superposing in the video display some computer-generated perspective grid lines, with equi-depth reference lines drawn from the reference grid to important objects, makes it easy for the observer to comprehend the relative depth of the objects.

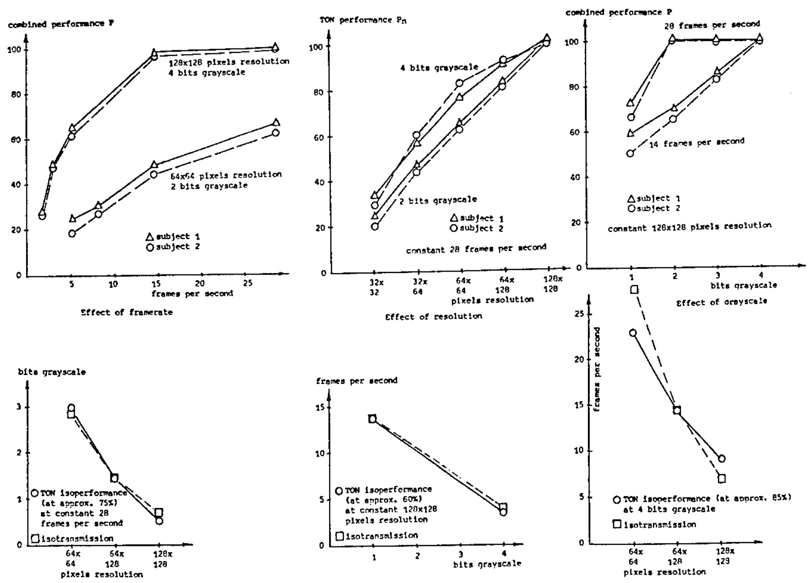

Figure 2. Ranadive's results for frame-rate, resolution, grayscale tradeoff. Top row, each plot shows performance as one of the three variables is improved, the other two kept constant. Bottom row, each plot compares constant (iso) performance and constant (iso) information transmission as a function of two of the three variables simultaneously, the other held constant. TON is take-off-nut task. [After Ranadive, ref. 4]

Superposing other essential graphics onto the video picture, much as the aircraft pilot's "head-up" display is superposed onto the windscreen, is a convenient way to save the human operator from having to keep accommodating from computer displays to video and back again.Computer-generated components of a display can be made to look realistic and then become "virtual displays."

Teleproprioception and Kinesthesis

Proprioception is literally "awareness of self". Gravity provides a strong vestibular cue and a directional static loading on one's own body, so that muscle reflexes are driven automatically to maintain posture and body-position awareness. With a teleoperator these cues are normally missing, or at least there is a severe problem of establishing anything approaching the tight coupling between proprioceptive sensors and brain. Kinesthesis is literally sense of motion. Kinesthesis and proprioception are terms often used together by psychologists, at least in part because the same receptors in the human body's muscles and tendons mediate both. For that reason we lump them together in our discussion.

Telekinesthesis and teleproprioception are particularly critical because, as telemanipulation experience has shown, it is very easy for the operator to lose track of the relative position and orientation of the remote arms and hands and how fast they are moving in what directions. This is particularly aggravated by one's having to observe the remote manipulation through video without peripheral vision or very good depth perception, or by not having master-slave position correspondence, i.e., when a joystick is used. Potential remedies are multiple views, wide field of view from a vantage point which includes the arm base, and computer-generated images of various kinds (the latter will be discussed further below). Providing better sense of depth is critical to telemanipulation anywhere.

Correspondence of display and control; anthropomorphic design

Closely related to teleproprioception and telekinesthesis is the question of whether there should be a one-to-one correspondence between displays (of whatever sensory modality) and the control devices upon which the operator directly acts with her hands (or feet or body). A fundamental principle of human-factors engineering is to design the controls and displays, insofar as possible, so that a control action and a resulting change in the display are in the same relative location with respect to the other controls and displayed variables, and move in the same direction. One way to ensure that this condition obtains is to design the teleoperator anthropomorphically — having the same form as the human operator — and then arrange at least the analogic controls (e.g., a master arm or joysticks), and perhaps even some of the symbolic controls, with geometric correspondence to what they control on the teleoperator. Of course a conventional identical master-slave system fulfills this condition.

The operator often must orient the teleoperator arm at a fixed location and orientation, for example a peg adjacent to and aligned with a hole. How well can this be done using a 2D video display? Yoerger [10] tested the operator's ability, viewing both directly and through video, to orient the slave hand normal to a plane when the plane was at different angles to the view direction. He found that there were significant orientation errors as a function of plane's orientation relative to view direction, and that for both direct and video viewing subjects consistently underestimated the angle between the view and the plane. A 45° angle between the view direction and the plane was found to be best.

If there is a 90° or greater rotation between hand movements and (lagged) displayed movements of the controlled object, performance in tracking and manipulation deteriorates. Bernotat [11] showed that adding an indicator of hand position to the rotated display improves tracking performance, but that the performance reverts when the hand-position cue is removed. Cunningham and Pavel [12] used an even more difficult 108° rotation of the display in a discrete aiming task, adding a novel "wind indicator" to the display which provided a virtual causation of the rotational bias. Subjects were instructed to oppose the virtual force represented by the indicator. This enhancement reduced aiming error by 70 percent in the first 10 minutes of practice, and aiming error did not rise after removal of the cue. This suggests that biases caused by display-control rotations can be overcome with proper cueing.

FORCE AND TOUCH SENSING AND DISPLAY

The nature of force feedback

Resolved force sensing is what the human body's joint, muscle, and tendon receptors do to determine the net reaction force and torque acting on the hand, i.e., the vector resultant of all the component forces and torques of the hand acting on the environment. Various limbs can perform this measurement over a wide dynamic range and with a just-noticeable difference of 6–8 percent in the 2–10 newton range. In force-reflecting master-slave systems such resolved forces are measured at the slave end either by strain-gauge bridges in the wrist (so-called wrist-force sensors), by position sensors in both master and slave (which, when compared, indicate the relative deflection in six DOF, which in the static case corresponds to force), or by electrical motor current or hydraulic actuator pressure differentials.

Display of feedback to the operator can be straightforward in principle; in force-reflecting master-slave systems the measured force signals drive motors on the master arm which push back on the hand of the operator with the same forces and torques with which the slave pushes on the environment. This might work perfectly in an ideal world where such slave-back-to-master force tracking is perfect, and the master and slave arms impose no mass, compliance, viscosity or static friction characteristics of their own. But not only does reality not conform to this dream; it can also be said that we hardly understand what are the deleterious effects of these spurious mechanical characteristics in masking the sensory information that is sought by the telemanipulation operator, or how to minimize these effects. Corker and Bejczy [13] showed that master and slave need not have the same kinematics if force reflection is to be used; a computer can transform coordinates ans still produce proper force feedback. It has also been shown that force reflection can be applied to a rate-control joystick [14].

Force feedback masking and teleoperation performance

There are several factors in master-slave teleoperation which contribute to insensitivity to contact or other forces. These can result in instability because the operator may not feel the forces imposed on the slave by the environment and will keep moving the master when force feedback should signal him to stop or to reverse direction.

There is effective masking of forces felt by the operator because the mechanism of the force-reflecting hand controller may have significant coulomb friction ("stiction") force F_C, viscous friction force F_V (F_C and F_V would not occur at the same time), inertial force F_i, and gravity force F_g between the force feedback actuators/sensors and the handgrip, all of which can cancel or, because they might be larger than feedback forces from the slave, confuse the operator as to what is their source. These masking forces add to the operator's own sensory threshold F_S for force detection. This effect is multiplied by whatever ratio R obtains for force feedback transferred to the master relative to forces applied to the slave by the environment. Combining these factors results in a net force threshold F_T:

$$F_T = R\,(F_C + F_V + F_i + F_g + F_S).$$

F_C and F_S are usually the major culprits.

Force reflection was inherent in the original direct mechanical cable-connected master-slave manipulators of Goertz [15], and was designed into the early electrical and hydraulic master-slave systems as noted earlier. Numerous studies have been performed over the years to evaluate whether, and under what circumstances, force feedback helps performance [16][17][18][19]. Massimino et al.[2] found that force feedback made a consistently significant difference and cut task-completion times almost in half.

Computer-graphic display of force-torque information

Force-torque information is easy to provide visually, though there is a question whether this is the best sensory mode to receive force feedback. Figure 3 shows a computer-graphic force-torque display developed by Bejczy [20]. The bars at the center provide a pseudo-perspective view of hand coordinates X, Y, and Z. The diagonal bar represents the Fx translational forces (in and out of screen). Bars at upper, right, and lower edges represent the moments around the X, Y, and Z axes, respectively. The two vertical bars on the left show finger opening and clamping forces.

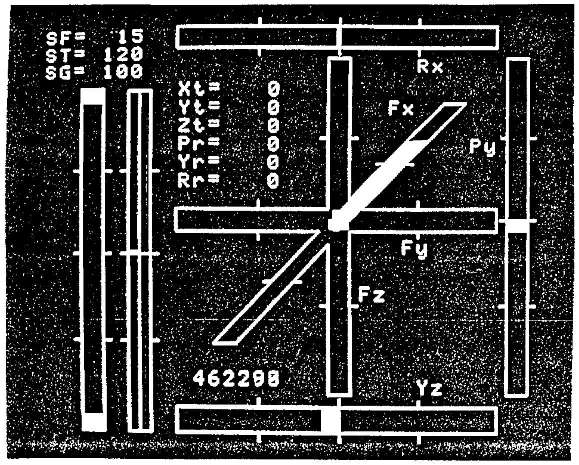

Figure 3. Bejczy's force-torque display. [Courtesy of Jet Propulsion Laboratory, California Institute of Technology.]

Sharing control between teleoperation and computer autonomy to achieve force control

Earlier some mention was made of trading and sharing of control between human and computer. Hayati and Venkataraman [21] developed an architecture for a flexible telerobot which shares control by a human operator using a full multi-degree-of-freedom position master and a semi-autonomous computer. Their scheme allows command signal vectors from both on-line teleoperator and computer to be weighted and added, where the weighting coefficients depend on factors such as time delay and whether the telerobot is operating in "free motion, guarded motion, fine motion, free force application, guarded force application or fine force application." For example, when in free motion, teleoperator inputs do not affect system stability, and thus can be allowed to dominate. However, in any force application or in guarded motion (i.e., where a contact surface is nearby) contact-force instability is likely, and thus teleoperator weighting is reduced. During fine motions teleoperation weighting is allowed along motion directions, but suppressed along other direction which may involve contact forces. The position and force feedback vector from the telerobot is similarly subjected to weighting matrices, where the coefficients are determined by criteria of stability and the separation of error contribution from each separate input agent. Figure 4 illustrates the weighting scheme. The weighting matrices are defined relative to the (preplanned) task space; each of six degrees of freedom can be set in one of ten modes independently, resulting in 10^6 combinations.

Comparison of task sharing with alternative control and force feedback modes

Hannaford et al. [22] performed an experimental evaluation of several command and sensory feedback modes including task sharing as just described above (one of the many combinations of control modes), using the Jet Propulsion Lab / Salisbury positional master arm and a Westinghouse Puma 560 robot arm serving as a slave. The five modes were (1) position control with visual feedback only, (2) position control with visual display of position and force (as described above in the subsection on

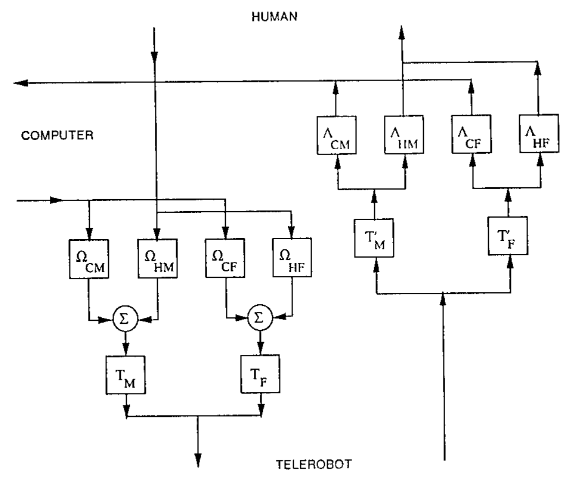

Figure 4. Weighting scheme of Hayati and Venkataraman (simplified by author) for sharing control between computer and human. Inputs from both computer C and human H are transformed by weighted control matrices for both the movement M and force F, then appropriately combined and subjected to Jacobian transformations T as shown. The reverse is done to provide feedback to the computer and human. [After Hayati and Venkataraman, ref. 21]

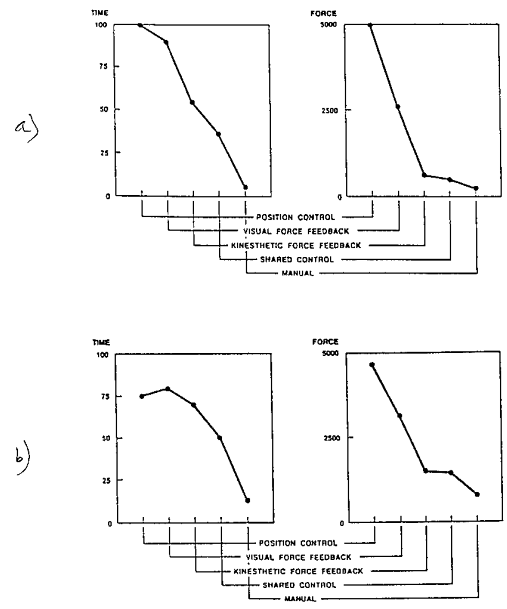

Figure 5. Hannaford's time and force results for task sharing with alternative control and force feedback modes. (a) Averaged completion time and force performance for peg-in-hole task. (b) Averaged completion time and force performance for electrical connector attachment task. [From Hannaford et al. , ref. 22]

graphical force display), (3) bilateral force feedback to the master arm (which they termed "kinesthetic control"), (4) shared control (based on the scheme just described above), and (5) direct bare-handed control. In this case of "shared control" the operator's force commands were added to those of automatic force accommodation for orientation axes and fine position control, while conventional force feedback to the human was used for free translation. They used four tasks in their experiments: attaching and detaching blocks covered with velcro, a matrix of peg-in-hole tasks with different size pegs and different size chamfers, mating and unmating several standard electrical connectors, and unmating, mating, and locking an electrical bayonet connector. Results are shown in Figure 5. In Figure 5, for two of the tasks the shared control proved significantly better in completion time than kinesthetic control, and the force levels (actually a sum of squared force integrated over time) even approached those for bare-handed ("manual") manipulation. Results from these experiments underscore that shared teleoperation and computer control is promising, but the number of arrangements yet to be evaluated is staggering.

Impedance control

Impedance is normally defined as the relation between applied force F and velocity V. For a linear system impedance Z is commonly defined as

$$Z = F / V = Ms + B + K/s$$

where M is mass, B is viscous damping, K is stiffness, and s is the Laplace argument or time-derivative equivalent in the time domain. This implies a common null point for all terms.

The variable stiffness (campliance) aspect of impedance control for a telerobot may be thought of in terms of a hypothetical "compliance frame" (Figure 6) attached to the end point of the teleoperator arm (master or slave side, whichever one chooses to consider). In this case it becomes clear that the compliance null point can be moved in position, while the compliance and/or viscosity parameters (mass is usually neglected) can be adjusted independently. Thus a relatively constant force may be applied to an object in spite of small arm motions relative to it by commanding the end point compliance to be soft and adding a large equivalent position bias in the desired force direction . Alternatively, a relatively constant position may be imposed on an object by a stiff spring (what we usually think of as position control). In fact, subject to constraints of stability and actuator limits, any desired end point impedance to motion (or admittance of forces) may thus be programmed to mimic the desired compliance, viscosity, and mass parameters of the end point. These parameters may even be different in different directions, or change with time — which seems to be what we do with our own limbs in catching balls, threading needles, and other ordinary manipulation tasks [23][24].

The best impedance for a master-slave manipulator

There is a diversity of opinion about what constitutes the "best" impedance for a master-slave teleoperator. One argument [25] is that an ideal teleoperator is one that is transparent, i.e., the equivalent of an infinitely stiff and weightless mechanism

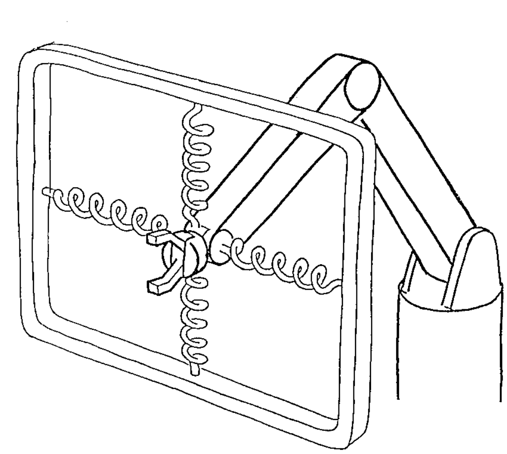

Figure 6. Hypothetical end-point compliance frame (equivalent to impedance felt by externally imposed forces). [From Sheridan, ref. 1]

between the end effector of the master arm and the operator's hand assembly of the master arm. Vertut and Coiffet [18] have suggested instead that operators get tired when holding their arms in fixed and awkward positions and/or applying constant forces (as master-slave systems often require), and the author's experience confirms this. Bejczy and Handylykken [19] report that there seem to be different best combinations of force-feedback gain (from slave to master) and feedforward gain (from master to slave) for different tasks.

Providing for the operator to adjust the impedance of the master and/or the slave may be a promising way of making a master-slave teleoperator more versatile than if the compliance-viscosity-inertance parameters remained fixed. A carpenter may carry and use within one task several different hammers, and a golfer many clubs, because each different tool provides an impedance characteristic appropriate for particular task conditions which are expected. Carrying many teleoperators into space, for example, may be avoided by making the impedance adjustable between slave and task and/or between human and master.

Should the impedance of the human arm serve as a model? The human arm has amazing capability. Also, as we shall see below, the impedance seen at the master port of a master-slave manipulator is to some extent dependent on the human operator's arm impedance. As Hogan [23] reports, much evidence supports the notion that the human arm can be modeled as having passive impedance. This model does not imply that the human arm is passive. However, the active part of the human arm dynamics can be considered as a state-independent force source that, at least in the linear case, does not affect the system's stability. At the same time, there is evidence that the human arm's impedance varies over a wide range, though the rapidity of adaptation may be limited. Perhaps the lesson from traditional manual control, namely the McRuer [26] crossover model could be applied to the human arm and manipulation task, namely that the combination of the arm and the task are much less variant than either by itself, and therefore the simplest and probably most useful model should be a model of the combination .

The skin senses of touch

Touch is a term used sloppily to refer to various forms of force sensing, but more precisely to refer to the sense of differential forces (or, equivalently, displacements) on the skin in time and in space, both normal and tangential to the skin surface. (The skin can sense other stimuli, of course, such as heat, cold, pain, etc.) The skin is a poor sensor of absolute magnitude of force, and it adapts quickly.

Five types of nerve fibers mediate touch [27][28]:

(1) Slowly adapting type I fibers terminate at the base of the epidermis in Merkel cells, are distributed densely (one per square mm), respond to temporal stimuli in the range 1–100 Hz, have a sensitive range of 0.03–3.0 mm skin indentation, and are acutely responsive to edges and regions of curvature.

(2) Rapidly adapting type I fibers terminate at the base of the epidermis in Meissner corpuscles, are also distributed densely (one per square mm), have a bandpass of 2–200 Hz with peak sensitivity near 50 Hz, have a sensitive range of 0.001–1 mm indentation, and are less spatially and temporally acute than type 1 above.

(3) Slowly adapting type II fibers terminate in deep Ruffini structures, are less densely distributed (10 per square cm), have low-pass temporal response (0–10 Hz), and are primarily responsive to horizontal skin stretch.

(4) Rapidly adapting type II fibers terminate in deep Pacinian corpuscles, have a temporal bandpass of 20–1000 Hz with peak sensitivity at 300–400 Hz, and are extremely sensitive (100–1000 angstroms peak to peak) to skin amplitude vibrations generally, much less at the receptor ending.

(5) Hair follicle receptors should also be added, which respond to light axial or bending forces, with spatial discrimination from 0.1–3 cm.

Touch sensing contexts and quantitative theory

Touch sensing and perception may be considered in three different sensorimotor contexts:

(1) Forces are imposed on the skin by the environment without any overt intentional movements made relative to the source of those forces. This may be called *passive* or *non-haptic* touch.

(2) The movements of the touch sensor are made voluntarily in order to explore some portion of the mechanical environment, and to achieve touch identification of one or more objects and their positions and orientations. This may be called *pure active* or *haptic* touch, where kinestheic sensation may be correlated with cutaneous sensation to infer patterns in time and space.

(3) Touch sensing is done as an integral part of actively manipulating with the hand or moving the body to perform some task not primarily one of touch sensing.

Context 1 may seem to be the equivalent of visual and electromagnetic image recognition and understanding. A great deal of quantitative theory has been applied to this problem for applications in robot vision, space photography of the earth and the heavens, biomedical imaging, etc. Unfortunately, cutaneous patterns do not seem to be perceived with enough resolution and memory to make much of this available theory applicable. Context 2 is now seeing some research in a telerobotic context, which may also offer a way into context 3.
Context 3 has produced little research that is coherent, not because it is not recognized as being an important problem, but because it is so difficult, and because the modes of "touching in the precess of doing" are so many and varied. To this writer's knowledge no generally accepted theoretical or experimental paradigms have emerged.

Though "labors in these lower vineyards of the sensory domain" [27] have not provided neat quantitative paradigms, the literature on touch perception is extensive. An excellent review is that provided by Loomis and Lederman [29], which includes determination of absolute and differential thresholds as a function of force magnitude and direction relative to the skin, time, frequency, body locus, two-point separation, stimulus size and shape (including texture), recognition among previously learned patterns, and the effects of masking on all of these.When discrimination and recognition are sufficiently large that multiple fingers and reshaping of the hand are required, that is called *stereognosis.*

Touch sensing and display devices

There are now a few devices for artificial *teletouch* sensing. Most of these have much coarser spatial resolution than the skin, such as the very first touch sensors for telerobots (which consisted of a few microswitches placed at gripping surfaces or where obstacle collisions might occur). Various devices have now been marketed (e.g, by the Lord Corporation) which are relatively coarse arrays of magnetic, resistive, capacitive, or optical continuous force/displacement elements. Harmon's [30][31] reviews of the state of tactile sensors for robots are surprisingly current.

The most difficult problem for teletouch is not sensing but display. How should artificially sensed pressure patterns be displayed to the human operator? One would like to display such information to the skin on the same hand that is operating the joystick or master arm which guides the remote manipulator. This has not been achieved successfully, the major reason being that the skin receptors are masked by the forces of gripping the handle as well as the reaction forces of inertia, friction, and spring-centering (if any) of the master. An option is to display to the skin at some other location than at the handle-gripping surfaces. Much of the early research in tactile displays was directed toward aiding the blind. Included have been arrays of electromagnet vibrators, piezoelectric bimorphs (up to 64x64 such bimorph vibrators have been packaged into a 7x7-inch array). More recently alloys such as TiNi which change their length when heated have shown promise.

Most of the success in teletouch has been achieved by displaying remote tactile information to the eyes using a computer-graphic display [32][33]. The above problems for tactile teleoperation are in spite of the fact that without vision one can easily track a randomly moving tactile stimulus almost as well as a visual one.

This was shown by Weissenberger and Sheridan [34], who used a handle lightly gripped between the thumb and the index finger to equalize the pressure, and by Jagacinski et al. [35] with a similar display.

TELEPRESENCE AND VIRTUAL PRESENCE

Telepresence

Telepresence is commonly claimed to be important for direct manual telemanipulation. It has yet to be shown how important is the sense of "feeling present" *per se* as compared to simply having high resolution, a wide field of view, and other attributes of good sensory feedback. Further, although telepresence is usually identified with direct manual teleoperation, it may be just as important to be able to "feel present" when supervising a semi-autonomous telerobot.

In addition to visual telepresence, there are auditory telepresence (binaural localization and spectral correspondence to the real world), resolved force (muscle force) telepresence, tactile (skin sense) telepresence, and vestibular telepresence (achievable through a motion platform driven by the same disturbances the operator would be subjected to were he at the remote, or virtual, location).

Many of the mechanical-force or other disturbances which might contribute to one's sense of telepresence are the very things one seeks to avoid. For example, one often seeks to avoid vibration or sudden unexpected mechanical forces which interfere with visual-motor skills. One seeks to avoid extremes of temperature and pressure, explosions, and other hazards which might contribute further to telepresence but which may be the very reasons for teleoperation in the first place. Therefore, "full" telepresence is a questionable goal in many situations.

Tachi's experiments in telepresence using a helmet-mounted display

Tachi et al. [36] developed and evaluated the hardware components to implement teleoperator telepresence (their term is *tele-existence*). At last report their head-mounted display was binocular, with 4-inch color liquid-crystal displays (320×220 pixels) and eyeglasses used to achieve close focus on the LCDs. The system was helmet mounted and weighed 1.7 Kg in all. An earlier system [37] used 3-inch CRTs in a 5- Kg assembly mounted in a five-DOF head-following servomechanism. With both systems they achieved good subjective report of telepresence. The second component of Tachi's system was a six-DOF electromagnetic sensor similar to the Polhemus sensor described above. It had three orthogonal 10-KH fields, and he achieved accuracies of 2.5 mm in translation and 0.5° in rotation within a 1.5–m^3 workspace. This drove a specially built seven-DOF slave robot which was purposely anthropomorphic in design to permit easy "tele-identification" with it. It also had a one- DOF torso rotation for slaving to the operator's waist twist. Figure 7 shows the operator with helmet-mounted display and the anthropomorphic teleoperator.

The third component was a three-wheeled remotely driven vehicle on which a pan-tilt-stereo video system was mounted [38]. The vehicle was driven by a manual joystick and the video driven by a head-mounted display, which also, of course, received the video signals. Auditory signals from microphones on either side of the vehicle were fed binaurally to the operator's ears. Actually the vehicle was also part of an autonomous vehicle navigation project. One of the justifications given for telepresence in such a vehicle was the need for the operator to help out the autonomous system when it runs into trouble and/or asks for assistance. In experimental evaluations with the vehicle it was found that many collisions occurred when a conventional video display was used, whereas the head-controlled stereo display improved performance significantly.

Synthetic window display

The head-mounted or helmet-mounted display is not the only

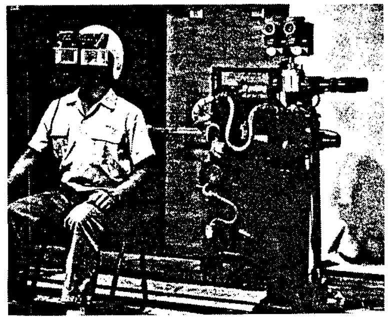

Figure 7. Tachi's experiments with head-mounted display for telepresence. Head , measured in 6 DOF electromagnetically or mechanically (6 DOF boom not shown), drives camera position, so that human's video display corresponds to viewpoint in remote environment. [Courtesy S. Tachi, Ministry of Trade and International Industry, Japan.]

way to achieve "geometrically correct" visual telepresence. The virtual window is another technique. Schwartz [39] describes a fixed high-resolution stereo-video system with head tracking, corresponding camera positioning, and image reproduction to each eye to correspond to what the viewer would see were he looking through a fixed window. Merritt [40] reports ongoing research to utilize both of these techniques in a sophisticated telepresence viewing system.

Virtual presence

When a computer-generated picture is substituted for the video picture and similarly referenced to the head orientation, the viewer can be made to feel present within an artificial world, which in addition to displays can include controls (which one actuates by moving one's hand to the corresponding locus in body-referenced space). The term *virtual presence* is used to describe such an arrangement. Synonyms, some of which seem self-contradictory, are *virtual environment, artificial reality,* and *virtual reality*. It may be said that systems to create virtual reality are now a reality. This can be attributed to the availability of computer graphic systems which are able to generate compelling object representations sufficiently fast, greatly improved head-mounted displays and optics, and position sensors such as the Polhemus, the VPL DataGlove, and the EXOS exoskeleton which can translate head and free limb movements into corresponding apparent movements of the computer-generated objects. Figure 8 illustrates the idea. Ellis [41] provides a sampler of recent research on pictorial displays for both virtual and "tele" environments.

NASA Ames and USAF Wright-Patterson virtual presence demonstrations

Over the last decade two virtual environment demonstrations were mounted simultaneously — one at NASA's Ames Research Center by Fisher and McGreevy and their colleagues [42], the other at the Wright-Patterson Air Force Base Aerospace Medical Research Laboratory by Furness and his colleagues [43]. NASA's development of a virtual environment workstation was justified as an experimental and developmental tool for eventual control of teleoperators with telepresence, as a control device for access and manipulation of data, and as a means to visualize physical flow and other computer-simulated phenomena in three dimensions. The NASA development concentrated on achieving a visually correct and comfortable head-mounted display and convincing computer graphics. The Air Force project was explicitly intended to investigate head-mounted display of real-time computer-generated images to a fighter pilot, who, instead of looking out at the (possibly weather obscured) real environment, could look around to see a clear virtual environment of mountains or other terrain (labeled as necessary), command trajectory, threat locations, etc. The Air Force project also concentrated on miniaturizing the head-mounted display system.

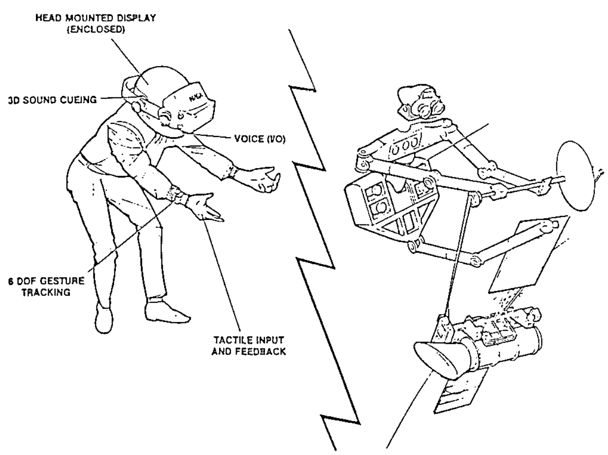

Figure 8. Operator wearing head-mounted visual and auditory display and instrumented gloves, experiencing virtual presence in fictional space environment generated by computer. [Courtesy NASA.]

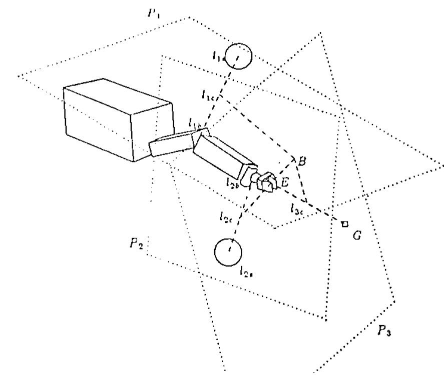

Figure 9. Computer-controlled "best view" of telerobot used by Das. Lines l_1, l_2, and l_3, respectively, are the distances from the teleoperator to the two closest obstacles (circles) and to the goal, G. Planes P_1, P_2 and P_3 are perpendicular bisectors of these lines. The "best" viewpoint is taken to be at the intersection of these planes (at B in the case shown) because it provides an orthogonal projection of these distances to the obstacles and to the goal. [From Das, ref. 48]

Virtual acoustic displays may play an important role in virtual presence. This is largely due to the "cocktail party effect" [44], the ability to resolve and identify meaningful sound patterns spatially even though their signal strength is but a fraction of the total sound energy entering the ear. On the basis of power spectral transfer functions for sounds reaching the eardrum from sources at different external locations (distortions due to head and pinna structures as well as room configuration and damping characteristics), an electronic device called the Convolvatron can produce in earphones a realistic experience of multiple sound sources as a function of head position and orientation [45].

Patrick [46] added a tactile buzzer to a VPL Data Glove and programmed it so that the wearer can "reach out out touch something" — in this case, when the index finger or the thumb or both are correctly positioned they feel a vibrotactile stimulus. Such a tactile display, however, gives the impression of touching a tuning fork, not an inert object. Kramer [47] has done a similar experiment with a mechanically servoed plate which pulls against the fingertip as the fingers close to create a virtual touch of a virtual object.

Teleproprioception by viewing a computer-modeled virtual environment

One of the most promising ways of achieving teleproprioception is through computer aiding. In this case the computer, when given the positions and orientations of teleoperator vehicle (base), arm and hand segments, environmental objects, and video camera view, can provide a synthesized view from any position and orientation selected by the operator. The viewpoint is no longer restricted by where the video cameras happen to be. The operator is free to "roam" arbitrarily to get a vantage point he likes, or to compare the views from several different points, perhaps using a joystick or other controller to "fly" her viewpoint around in simulated space.

Das [48], in the context of his above-mentioned experiments with computer-simulated telemanipulation, systematically compared this free selection technique with three other views. A second view was fixed just above the manipulator base, as though the operator were viewing through a window from inside the vehicle. A third view was fixed in space to one side of the task and some distance away. And a fourth view was selected by a "best view" algorithm. The algorithm assumed the operator wants a true projection of three relative distances: from manipulator end point to the target and to the two closest obstacles. For any one of these distances, an equally good viewpoint was anywhere on the plane bisecting the line drawn between the two objects, e.g., the end point and the target. Thus there were three planes to consider. The intersection of the three planes was taken to be the "best" viewpoint. Figure 9

Das' results showed that, in terms of speed and obstacle avoidance, performance was best when the operator could select the view. The automatically selected view and the fixed point beside the task were less good for most subjects, but one novice did best with the automatic view. The view "out the window" was worst.

One interesting application of virtual reality is surgical training, and a specific example of that is simulation of arthroscopy (surgery on bones and joints by using surgical instruments and fiber optics inserted through the patient's skin). In such a simulation, the arthroscopist trainee sees on a computer screen (as though through an optical fiber bundle inserted in, say, a knee joint) a knife or tweezer or both (as though inserted from another direction) as well as cartilage, muscle tissue, and bone. The trainee holds a simulated surgical instrument and makes a cut, at the same time seeing the knife cut through cartilaginous tissue and feeling the viscous reaction forces. When the "knife" hits the bone he sees it stop and at the same time feels it up against a hard surface. The mechanical design of such a multi-DOF virtual environment tool and the generation of high-bandwidth forces which correspond accurately to real force feedback is a difficult problem, as is the algorithmic modeling of impedance characteristics for various kinds of animal tissue. K. P. Chin explored this mixture of visual and tactile virtual environments in unpublished experiments performed at the MIT Human-Machine Systems Laboratory.

Design criteria for visual telepresence and virtual presence

High-quality visual telepresence or virtual presence requires that the viewed image follow the head motion with no apparent lag or jitter (this is a servo-control problem and has been hard to achieve in existing systems), that an object in the display subtend the same retinal angle as it would in direct vision, and that motion parallax and other head-motion cues also correspond to direct viewing. Other problems are in achieving sufficient field of view (it should be at least 60°), depth of field, correct focal length, image separation for stereoscopic fusion, and luminance, resolution, color, and other image-quality factors, particularly at the fovea. When the image is computer-generated, additional problems lie in achieving sufficient image-generation speed and frame rate, grayscale, and variable accommodation (in contrast to fixed focus at infinity). As one might expect, there are also serious problems of cost, size, and weight.

It is natural to seek an objective measure or criterion that can be

used to say that telepresence or virtual presence have been achieved. However, telepresence (or virtual presence) is a subjective sensation, much like mental workload, and it is a mental model — it is not so amenable to objective physiological definition and measurement. Some might assert that a subjective report from the person having the experience is the only measure. An objective criterion might be a test analogous to that for computer intelligence attributed to Alan Turing: if the observer cannot reliably tell the difference between telepresence (or virtual presence) and direct presence, then the telepresence (virtual presence) has been fully achieved. A practical criterion of telepresence proposed by Held and Durlach [49] is the degree to which the observer responds in a natural way to unexpected stimuli — e.g., by blinking her eyes or ducking her head when he sees that an object is about to hit her. We are far from meeting this strict criterion in most applications.

Three independent determinants of the sense of presence

In consideration of what Held and others have suggested, Sheridan [50] proposed that there are three principal and independent determinants of the sense of presence: *extent of sensory information* (the transmitted bits of information concerning a salient variable to appropriate sensors of the observer), *control of relation of sensors to environment* (e.g., ability of the observer to modify her viewpoint for visual parallax or visual field, or to reposition her head to modify binaural hearing, or ability to perform haptic search), and *ability to modify physical environment* (e.g., the extent of motor control to actually change objects in the environment or their relation to one another).

These determinants may be represented as three orthogonal axes (see Figure 10), since the three can be varied independently in an experiment. Perceived extent of sensory information is sometimes regarded as the *only* salient factor. Lines of constant information communicated are suggested in the figure to indicate that the "extent of sensory information" is a much greater consumer of information (bits) than the two control components, "control of sensors" and "ability to modify environment."

Given the three independent determinants of presence, the larger research challenge is the determination of the dependent variables: sense of presence (as measured by subjective rating and by the objective measures suggested above), objective training efficiency, and ultimate task performance.

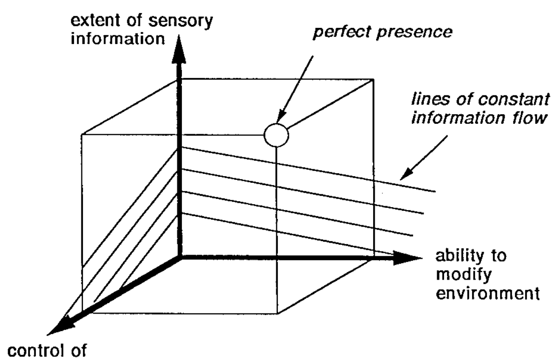

Figure 10. Three components of presence. Hypothetical lines of constant information suggest that for purposes of providing a sense of presence, information channels are better used for control of sensors and modification of the environment than for higher resolution displays. [From Sheridan, ref. 50]

Jex's criteria for "feel" of hand controls and time delay in simulators

The above discussion of telepresence and virtual presence was based primarily on visual considerations. What can be said of proper telepresence conditions for force feedback? There is considerable experience with force feedback in aircraft and automobile simulators, where reproducing the feel of hand controls' feedback is a high priority.

Jex [51], based on much experience with aircraft and automobile simulators, posited the following four critical tests for achieving virtual reality in the "feel" of hand controls (control sticks in aircraft, steering wheels in automobiles — what Jex calls "manipulanda"):

• With all other simulated forces set to zero, when the mass or inertia of the simulated hand control is set to zero, it should feel like a stick of balsa wood (i.e., have negligible lag, friction, jitter, or forces) up to the highest frequency that a finger grip can impose, or about 7 Hz.
• When pushed against simulated hard stops, the hand control should stop abruptly, with no sponginess, and it should not creep as force continues to be applied.
• When set for pure Coulomb friction (i.e., within a non-centering hysteresis loop), the hand control should remain in place, without creep, sponginess or jitter, even when repeatedly tapped.
• When set to simulate a mechanical centering "detent" and moved rapidly across the detent, the force reversal should be crisp and give a realistic "clunk" with no perceptible lag or sponginess.

Jex has also concluded that for a wide range of simulations in which operator steering of a vehicle is involved, in order to keep mental workload and performance within acceptable bounds, any simulation delay artifact must be less than about one-fourth of the effective operator response delay.

MANUAL CONTROL

Classical models of manual control and movements

Since roughly 1950 there has been much effort devoted to using conventional linear control theory to model simple manual control systems (Figure 11), where the human operator is the sole in-the-loop control element and the controlled process can be represented by linear differential equations. A primary motivation for this work was the need to establish predictive models for control of aircraft, where having good differential equation models for the controlled process (airframe plus control electromechanics in this case) was of no use unless models of the pilot were factored in as well. Initially it was believed that an independent model of the pilot was appropriate, so that the pilot model could then be combined with whatever controlled process was of interest. This was soon found to be impractical, since the characteristics of the human operator proved to be very much *dependent* upon the controlled process, varying to compensate for the controlled process so as to stabilize the closed-loop system and provide satisfactory transient response.

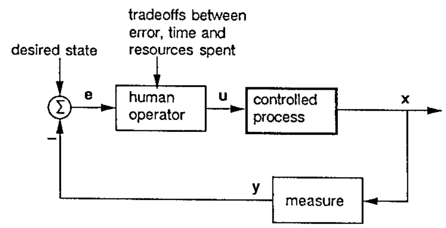

Figure 11. Simple compensatory manual control paradigm. Action **u** causes simple nulling of error **e** between current measured state **x** and desired state (goal).

It was then proposed to model the human operator and the controlled process as a single forward loop element, to combine the two upper blocks of figure 11. The idea was that there would be only minor variation of the combined human and process from application to application. This approach proved very successful. The result is the *simple crossover model* of McRuer and Jex [26] which has the form

$\mathbf{x/e} = Ke^{-j\omega T} / j\omega$.

This is essentially a combined pure time delay and integrator, ω being frequency. The (small) variations of parameters K and T are well established in the literature. What is important here is the idea of a model in which *human operator plus controlled process is what is invariant*, not the human operator *per se*.

Hick [52] proposed a model, based on Shannon's [53] information theory, for the time it takes to choose which of several alternative movements, i, to make when the choice is based on an immediately displayed signal calling for that move, and the move time itself is brief and constant:

$$H_{choice} = \Sigma_i\, p_i \log_2(1/p_i), \quad T_{choice} = \alpha + \beta\, H_{choice}$$

where H_{choice} is information in bits, p_i is the probability of signal i, T_{choice} is the time required to choose, and α and β are scaling constants dependent on task conditions. α includes at minimum the base reaction time for making the slightest hand movement in response to a visual stimulus.

Fitts [54] also used the information measure for his model of the time required for making a discrete arm movement :

$$H_{move} = \log_2 (2A / B), \quad T_{move} = \alpha + \beta\, H_{move}$$

where (see Figure 12) H_{move} is information in bits (sometimes also called *index of difficulty*), A is the distance moved, B is the tolerance to within which the move must be made (for Fitts' experiment a tap between two lines), T is task completion time, and α and β are again scaling constants, different for different conditions. Fitts probably did not realize what wide application the model would find. When applied to simple one-dimensional movements to within tolerances, the model has withstood the test of time and been robust over a wide range of A's, B's, and other task conditions such as bare-handed vs. master-slave manipulator It was successfully fitted to experimental data in a number of the studies described above. However, like so many elegant models for human behavior, Fitts' model breaks down for more complex manipulations.

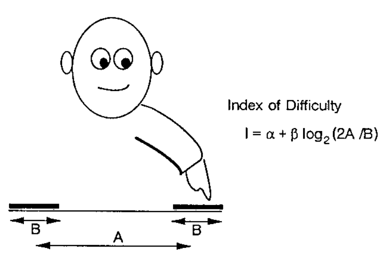

Figure 12. Fitts' experiment for moving a given distance to within a given tolerance. [From Sheridan, ref. 1]

If a person must first make a choice and then move, a first-order model for time required will then be

$T_{total} = T_{choice} + T_{move}$.

Thompson [55], in his studies of manipulation, showed that the time required to mate one part to another was a function of the degrees of constraint (the number of positions and orientations that simultaneously have to correspond before the final mating could take place). Figure 13 illustrates the idea of degrees of constraint. Data based on both the Fitts and the Thompson measures will be shown later when time-delayed manipulation is discussed.

Operator hand controls

The most popular operator hand controls are the articulated master arm and the joystick.

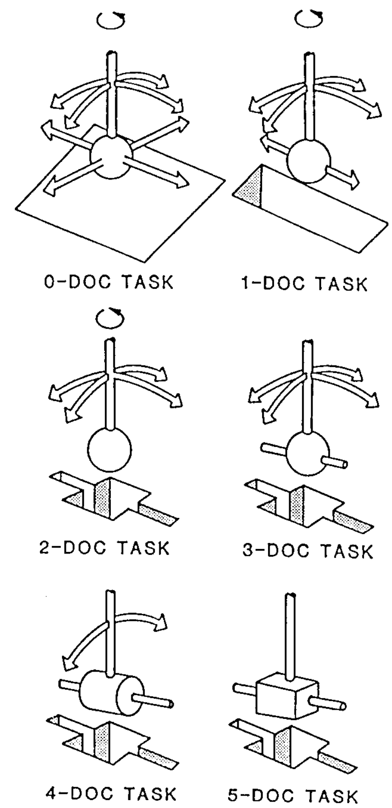

Figure 13. Thompson's degrees of constraint. [From Thompson, ref. 55]

Most articulated master arms have been used for master-slave positioning. Usually these have been kinematically isomorphic to the slave in construction. They need not be, however, so long as they have the same number of DOF as the slave and as long as the end-point direction of motion of the master and the slave correspond — the computer can do the coordinate transformations. The master should be sized to the convenience of the operator — it need not be the same size as the slave. Its full range of motion must conform both to the available space and to the operator's reach; at the same time there must be enough movement that small random muscle movements do not produce significant command signals. These constraints on both ends limit the dynamic range. Master arms as small as 1 foot in total length are in use. Master-slave position control provides quick and natural repositioning, but relatively poor ability to move very slowly.

The joystick is commonly available in up to three degrees of freedom, is normally spring centered, and commands an end-effector (or vehicle) rate proportional to joystick displacement. It can also command acceleration. There is usually kinematic resolution by computer, so that end-effector movement direction corresponds to joystick movement independent of the arm configuration. A slight electrical dead-zone is usually added to prevent inadvertent drifting of the arm in any particular direction. The joystick permits high positioning accuracy, but at the cost of relatively slow repositioning movements. In six- DOF applications two joysticks have typically been used: one to command translation in three DOF and one to command rotation in three DOF. There have been several six-axis joystick designs, one of which (developed by the German firm DLR) uses optical transducers, and a similar device called the "Space Ball" in the US. Mostly these are isometric devices (very stiff "force-sticks"). There has been some question about how well an operator can use such a device to control all six axes at once.

Massimino et al. [56] experimentally measured human tracking capability using such a six-axis "sensor-ball" to keep two virtual spheres aligned horizontally and vertically and of the same size (front-back indication) and to keep tcross hairs on the cursor and the target together. They found that translational movement perpendicular to the display screen produced significantly more RMS error than did horizontal or vertical translations. Performance in rotational DOF did not differ significantly from one to another. Rate control was better than acceleration control, as expected. With more simultaneous DOF, performance on any one axis deteriorated. Figure 14 illustrates the translation results.

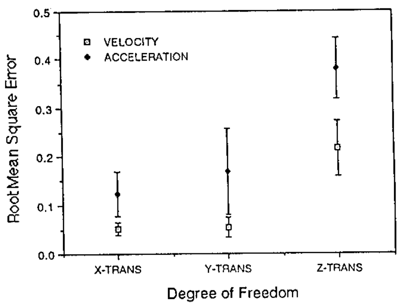

Figure 14. Massimino's results of tracking with six-axis sensor ball. Subjects simultaneously tracked in all 6 degrees of freedom. The graph shows the component translation errors in x, y and z. Data points are averages of six subjects. Vertical lines indicate one standard deviation. [From Massimino et al., ref. 56]

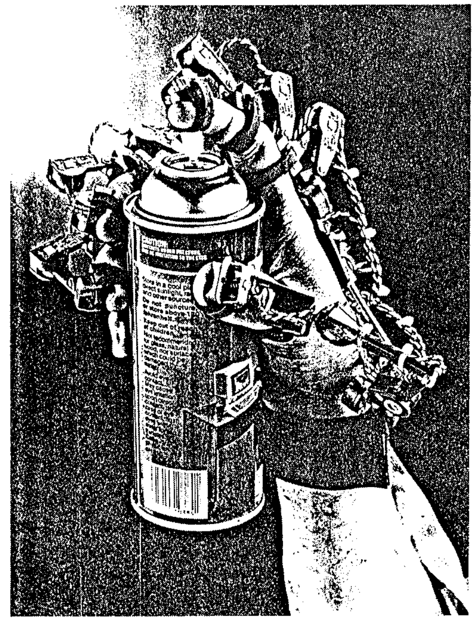

Figure 15. EXOS hand goniometer. [Courtesy of Exos Corp.]

Some newly developed commercial sensors that can be used to do six-axis positioning have the advantage over the conventional master-arm that they can be positioned freely in space without a mechanical link to a fixed base. The Polhemus sensor is a six-DOF electromagnetic system consisting of a transmitter and a receiver, each slightly bigger than a cubic centimeter. When one is moved relative to the other, provided they are not separated by more than a meter and provided there is little interference from nearby metal objects, the change in their relative position is measured in all six DOF to within several millimeters in translation and roughly 1° in rotation.

The VPL DataGlove is a nylon glove worn by the operator. It has optical fibers embedded on the dorsal side of each finger and the thumb. When any joint flexes, light passing through the optical fiber serving that joint is reduced because of scattering, and this is a measure of the flexure of the optical fiber. Unfortunately the glove tends to slip on the skin, the bends of the fibers do not coincide one-to-one with the operator's finger-joint rotations, and both may have different kinematics from the teleoperator hand being used. Therefore the control of teleoperation is neither precise nor consistent, and it may be necessary to perform rather complex calibrations in order for satisfactory open-loop mapping from operator hand pose to teleoperator hand pose to be achieved [57][58]. The Exos articulated multi-DOF hand goniometer (Figure 15) serves a similar function but consists of a pin-jointed multi-segment exoskeleton worn on the hand, with Hall-effect sensors to measure joint rotations. It is bulkier but more accurate than the DataGlove.

Using other body limbs and the head to signal the computer

Body limbs other than hands have been used as means of control , the most common example being the clutch, brake, and accelerator pedals of automobiles. The lower limbs, because of their mass, are not the fastest means of control, but they do give the advantage of large force capability, which was a good reason for assigning them to operate brake and clutch pedals prior to the time of power assist.

Head motion and eye motion are other means for the operator to signal the computer. Head motion can be measured by mechanical linkages attached to helmets or by electromagnetic or optical trackers. Eye tracking instruments are now readily available and of high quality, and are widely used to measure eye scan paths. Mostly these follow a pattern of 50-msec saccades (rapid movements which are quite unpredictable in direction and extent of movement and which seem to depend on the information "of interest" in the image) followed by 200–500-msec dwell periods, during which the brain presumably reads in the information.

Operator-resolved and task-resolved coordinates

Operator-resolved manipulation means that the operator can move or rotate her own hand and have the teleoperator end effector move or rotate in the same direction, independent of the kinematic configuration of the master or slave arm segments or joint positions. This is achieved by using the Jacobian [59] for resolving the velocity of the slave in correspondence to the velocity of the master.

Task-resolved manipulation means that the operator can order the teleoperator end effector to move or apply force in a coordinate system referenced to a normal to the surface of a large object or environmental structure such as a ship or a pipe [60]. This requires sensing that surface in the process of manipulating and continually performing coordinate transformations to update the axes with respect to which the operations are being done This is an extension of end-point resolution — ability to command the finger to move in a desired trajectory without having to worry about how to move all the joints between the finger and the shoulder.

COPING WITH TIME DELAY

Why there is a problem

Continuous teleoperation in earth orbit or deep space by human operators on the earth's surface is seriously impeded by signal transmission delays imposed by limits on the speed of light (radio transmission) and computer processing at sending and receiving stations and satellite relay stations. For vehicles in low earth orbit, round-trip delays (the time from sending a discrete signal

until any receipt of any feedback pertaining to the signal) are minimally 0.4 seconds; for vehicles on or near the moon these delays are typically 3 seconds. Usually the loop delays are much greater, approaching 6 seconds in the case of the earth-orbiting space shuttle because of multiple up-down links (earth to satellite or the reverse) and the signal buffering delays which occur at each device interface. A similar problem is encountered with remote control in the deep ocean from the surface if acoustic telemetry is employed to avoid dragging miles of heavy cable. Because sound transmission is limited to around 1700 m/sec in water, communicating over a 1700-m distance poses a 2-sec round-trip delay.

Continuous closed-loop control over a finite time delay is not possible, because any energy entering the loop at such a frequency that half a cycle is equal to the time delay will result in positive feedback rather than negative, so that if the loop gain exceeds unity at this frequency (which it normally would at low frequency) there is an inherent instability. Of course in the case of supervisory control, wherein commands are sent by the human operator through the time delay to a computer, the computer then implements the commands by closing loops local to itself, reporting back to the supervisor when the task is completed. The computer's local loop closure has no delay in it and therefore causes no instability. Nor, because of the intermittent nature of the supervisor's control, does the delay in her command-feedback loop cause instability.

Early experiments with time delay

With such delays in a continuous telemanipulation loop, it has been shown experimentally that the time for a human operator to accomplish even simple manipulation tasks can increase manyfold, depending upon the time delay and the complexity of the task. This is because the human operator, in order to avoid instability (which is quite predictable from simple control theory), must adapt what has come to be called a "move and wait strategy," wherein he commits to a small incremental motion of the remote hand or vehicle, stops while waiting (the round-trip delay time) for feedback, then commits to another small motion, and so on.

Ferrell [61] was the first to demonstrate experimentally the predictability of teleoperation task performance as a function of the delay, the ratio of movement distance to required accuracy , and other aspects of delayed feedback in teleoperation. Ferrell's results (Figure 16) are for simple two-axis-plus-grasp manipulations on a table. Black [62] performed similar experiments with a conventional six-axis-plus-grasp master-slave manipulator.
Thompson [55] showed how task-completion time was affected not only by time delay but also by degrees of constraint (see Figure 13). Thompson's experimental results are shown in Figure 17.

This problem has discouraged control of space vehicles from the ground. However, as more and more devices are put in space, the requirements increase for humans to perform remote manipulation and control, and if this can be done entirely from earth there are great savings in dollars and risk to life.

Early predictor displays

"Predictor displays," where cursors or other indications driven by a computer are extrapolated forward in time, are of two types. A first is based upon current state and time derivatives — i.e., Taylor-series extrapolation. A second involves inputting current state and time derivatives, as well as expected near-future control signals, into a model [63]. Such displays have been employed in gunsights, on ships and submarines, and as "head-up" optical landing aids for aircraft pilots. When there is significant transmission delay (say more than 0.5 sec) and a slow frame rate (say less than one frame per 4 seconds), a predictor display can be very useful. Both of the latter conditions are likely to be present with long-distance acoustic communication.

Verplank [64] implemented an experimental predictor of the second type for a simulated planetary rover. A computer model of the vehicle was repetitively set to the present state of the actual system, including the present control input, then allowed to run at roughly 100 times real time for a few seconds before it was updated with new initial conditions. During each fast-time run, its response was traced out in a display as a prediction of what would happen over the next time interval (say several minutes) "if I keep doing what I'm doing now." Such techniques are adequate for continuous control of single-entity or "rigid body" vehicles, but not for telemanipulation, where it is necessary to predict,

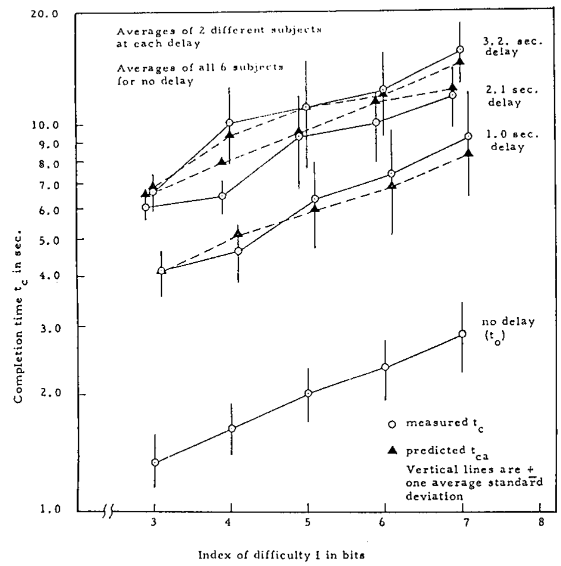

Figure 16. Ferrell's results for time-delay in telemanipulation. Experiments were performed in simple two-DOF grasp-and-place tasks with various accuracy requirements (Fitts' index of difficulty) and pure time delays. [From Ferrell, ref. 61]

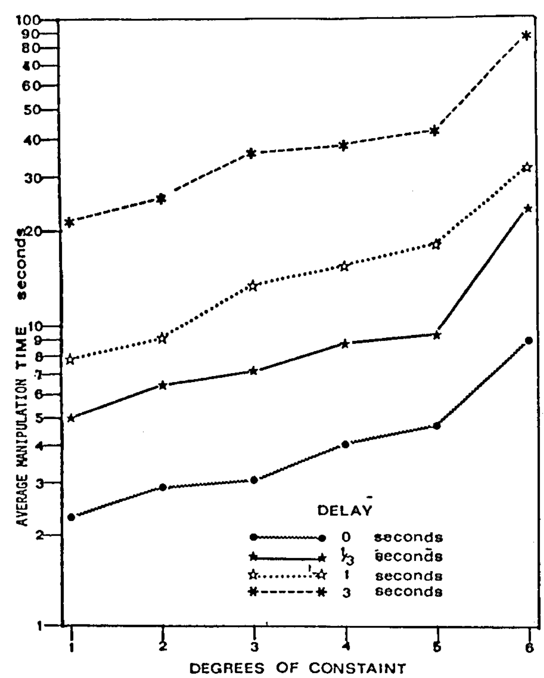

Figure 17. Thompson's results for time delay and degrees of constraint (defined in figure 13). Averaged times include transport of peg to hole, positioning, and inserting. [From Thompson, ref. 55]

(a)

(b)

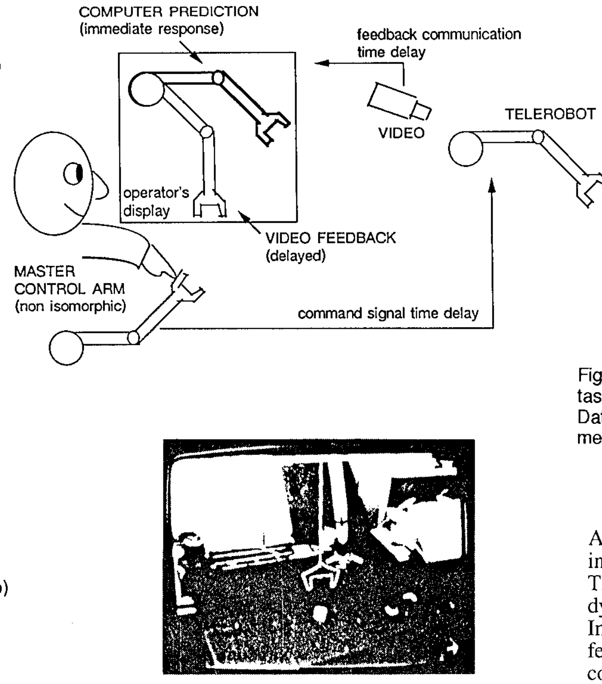

Figure 18. Noyes' telemanipulation predictor display. (a) Diagram of experimental setup. (b) Photograph of stick figure arm superposed on video screen. [From Noyes , ref. 65]

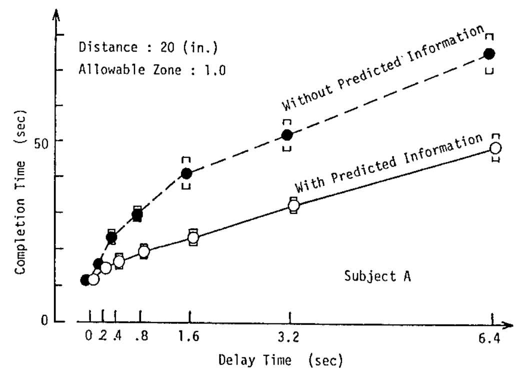

Figure 19. Hashimoto results for predictor display evaluation in simple task of repositioning a block 20 inches to within a one inch tolerance. Data shown are for one subject. Brackets are standard error of the mean for repeated trials. [From Hashimoto et al. , ref. 68]

relative to the environment, the simultaneous positions of a number of parts — i.e., a spatial configuration in multiple degrees of freedom, not just a single point.

Noyes [65] built the first predictor display for telemanipulation, using newly commercially available computer technology for superposing artificially generated graphics on to a regular video picture.The video picture was a (necessarily simulated) time-delayed picture from the remote location, generated as a coherent frame (snapshot) so that all picture elements in a single scan were equally delayed. (Otherwise the part of the screen refreshed last would be delayed more than the part refreshed first.) As shown in Figure 18, the predictor display was a line drawing of the "present" configuration of the manipulator arm or vehicle or other device. The latter was generated by using the same control signals that were sent to the remote manipulator (device) to drive a kinematic model of it. The computer model was drawn on the video display in exactly the same location where it would actually be after a one-way time delay and where it would be seen to be on the video after one round-trip time delay. Since the graphics were generated in perspective and scaled relative to the video picture, if one waited at least one round-trip delay without moving, both the graphics model and video picture of the manipulator (device) could be seen to coincide. The effectiveness of these techniques was demonstrated for simple models of the manipulator arm and simple tasks [65][66][67][68]. With such a display, operators could "lead" the actual feedback and take larger steps with confidence, reducing task performance time by 50% (Figure 19).

Two, more elaborate, predictor instruments

When the motion of vehicles or other objects not under the operator's control can be predicted, e.g., by the operator's indicating on each of several successive frames where certain reference points are, these objects can be added to the predictor display. With any of these planning and prediction aids, the display can be presented from any point of view relative to the manipulator or vehicle — which is not possible with the actual video camera.

A prediction architecture proposed by Hirzinger et al. [69] includes this notion (Figure 20) as well as dynamic prediction. The stick-figure overlay on the delayed video is driven by a dynamic model (whereas Noyes et al. used a kinematic model). In the figure this is constituted by the sum of the A and/or B feedback coefficients operating on correspondingly delayed commands. In the middle of the diagram is the implementation of the canonical first-order $x(k+1) = Ax(k) + Bu(k)$, where k corresponds to what is going on instantaneously with the space telerobot. The $x(k+1)$ estimate is corrected in the usual way by Kalman gain-multiplied discrepancy between estimated $y(k-nd)$ and the corresponding actual downlink signal. The delay line on the right side is required to estimate $y(k-nd)$. By estimating $x(k)$ — i.e., what is happening in space — activities such as rendezvous and docking can be coordinated with clock-determined events which are not under the control of this human operator.

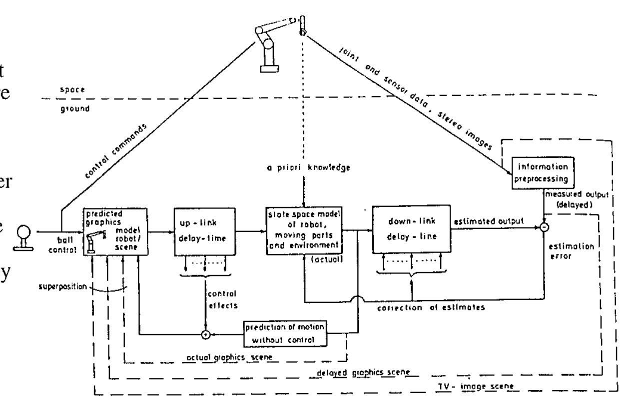

Figure 20. Hirzinger's predictor incorporating adaptive model. [After Hirzinger et al., ref. 69]

Another predictor instrument was developed by Cheng [70] as an aid to human operator control of the Woods Hole Oceanographic Institution's remotely operated submersible *Argo*. Essentially the latter is a heavy vehicle suspended and passively towed by a very long cable (up to 6000 m) from a support ship. The time constant for changes in control from the ship to become manifest in the position of the submersible is of the order of 10 minutes. To predict the submersible's trajectory in latitude and longitude from steering control actions performed on the ship, the model for the predictor must include the submersible, the cable, and the ship

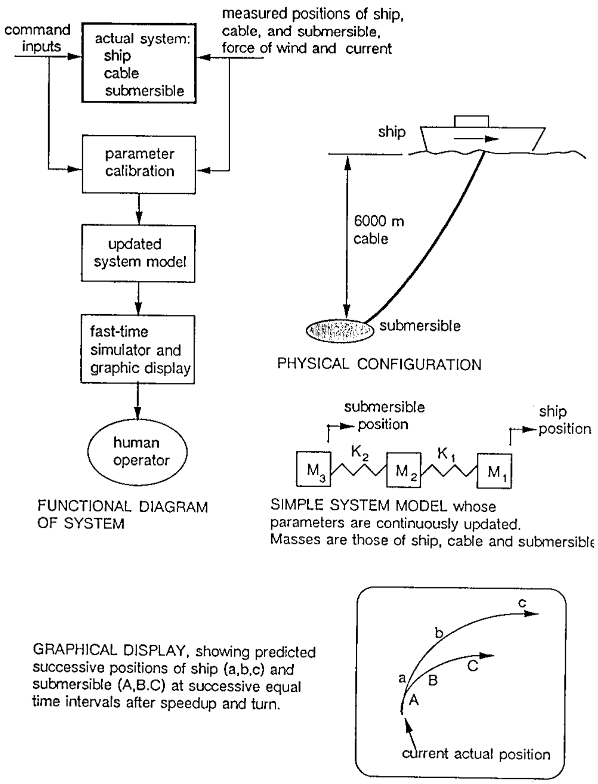

Figure 21. Cheng's adaptive predictor for towed submersible. [From Cheng, ref. 70]

(all fairly nonlinear), and must account for both wind and water current disturbances. The cable was the most difficult to model, but it was found that a relatively simple linear model whose parameters are continuously updated (see Figure 21) does a rather good job. In simulation trials, such a model cut the error in following a given trajectory to one-third. With the predictor display, human operator control actions were at significantly lower levels of thrust than without the predictor, a result consistent with theoretical analysis which suggested that the predictor effectively lowers the gain and increases damping.

Time-delayed force feedback

Force feedback with time delay is a different problem from that with visual feedback. Ferrell [71] showed that it is unacceptable to feed resolved force continuously back to the same hand that is operating the control. This is because the delayed feedback imposes an unexpected disturbance on the hand which the operator cannot ignore and which, in turn, forces an instability or the process. With visual delay the operator can ignore the disturbance and can avoid instability by a move-and-wait strategy or by supervisory control [61].

Since Ferrell's experiments there have been various proposals, the simplest of which is to display force feedback in visual form on a computer display. Alternatively the force feedback can be to the hand that is not on the master hand or joystick. Another suggestion has been to feed back disturbances greater than a certain magnitude to the controlling hand for a brief period, at the same time cutting off or reducing the loop gain to below unity, and subsequently to reposition the master to where it was at the start of the event. Finally, there is the possibility of predicting the force feedback to compensate for the delay, and feeding the predicted force but not the real-time force back to the operator's hand.

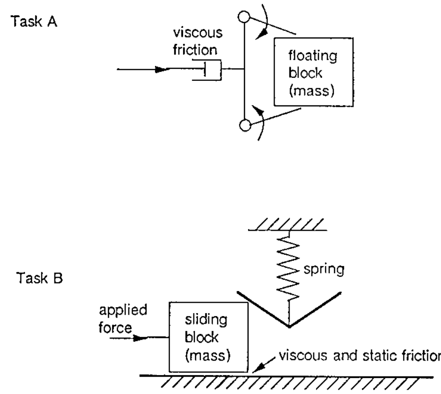

Figure 22. Buzan's tasks for time-delayed force feedback experiments. In task A, human subject was to reach out and grasp block (which was freely floating in space) without inadvertently accelerating it out of reach before grasp could be achieved. In task B, human was to push block to center of spring-clamp until light static friction held it there and not let it pop out the other side. Models used to generate predictor displays were simplifications of (simulated) real-time tasks (e.g., no static friction in task B). [From Buzan, ref. 72]

Buzan [72][73] evaluated the latter approach experimentally. He employed an open-loop model-based prediction to drive both a visual predicted-position display and a force exerted back on the operator through a master positioning arm. He did his experiments with a one-DOF teleoperator system, a 3-second time delay, and two challenging computer-simulated tasks. The first task was to extend the arm to make contact with (and unavoidably accelerate) a floating mass, then grasp it with a discrete action (an additional "half" DOF) before it "got away." The second task was to push an object into a "stiff slot" with enough force to get it in and have static friction hold it there, but not so much force that it goes right out the other side. Figure 22 illustrates the second task.

Buzan tried three force-feedback-display techniques. In one, which he called *direct force feedback*, he simply presented the predicted force (but not the delayed "real" force) to the active hand, the hand commanding the teleoperator position. In a second method, which he called *dual force feedback*, he presented the delayed force to an inactive hand and the predicted force to the active hand. In the third display technique, which he called *complimentary force feedback*, he presented to the active hand the sum of a low-pass-filtered delayed force feedback and a high-pass-filtered predicted force feedback.

Buzan's results showed, among other things, that end-point impedance made a big difference in these tasks. The contact-and-grasp task was easiest with a soft end point compliance, while the slot task favored a stiff end-point. Buzan also found that the complementary force feedback proved difficult to use. When the visual predictor was used and was perfect, the predicted force feedback had a negligible effect on performance. When telemanipulation was blind, both the direct and the dual force feedback worked quite well, enabling the operator to do the tasks where he otherwise could not.

Sensory substitution

As is well known, when there is force feedback in a control loop with time delay, the force reflected to the hand, unless the hand is infinitely stiff, simply reenters the control loop, producing an instability, provided the gain is greater than unity. A circumvention of this is to have the feedback of force be other than an actual unbalanced physical force to the hand. Massimino [74] tested this concept for the teleoperation task of inserting a four-sided peg into a four-sided hole. Using in one case vibrators on the skin (four vibrators in a square, the amplitue of vibration corresponding to the interactive force between the peg

and the corresponding side of the hole), and in another case auditory tones (high and low pitch for contact with top ond bottom of hole, left and right ears for contact with left and right sides of the hole). Results showed clear advantages of sensory substitution in either auditory or vibratory form when time delay otherwise would cause instability.

Time and space desynchronization in a predictor/planning display

Conway, Volz, and Walker [75] extended the predictor idea of Noyes and Sheridan [66] and combined it with a planning model in what they call "disengaging time-control synchrony using a time clutch" and "disengaging space control synchrony using a position clutch." In their scheme, the *time clutch* allows the operator to disengage synchrony with real time, to speed up making inputs and getting back simulator responses for easy maneuvers and to slow down the pace of such commands and simulator responses for hard maneuvers where more sample points are needed. The computer buffers the command samples and later feeds them to the actual control system at the real-time pace, interpolating between sampled points as necessary. (This is not unlike the "speeding up on the straightaways and slowing down on the curves" example previously cited as an advantage of preview control, and in fact is what anyone would do in making best use of planning time.) The only requirement is that the progression of planned actions must keep ahead of what must be delivered "right now" for real-time control (and also take into account any time delay).

Disengaging the *position clutch* allows one to move the simulator in space without committing to later playback, this for the purpose of trying alternative commands to see what they will do. Disengaging the position clutch necessarily disengages the time clutch and creates a gap in the buffer of command data. Reengaging the position clutch may require path interpolation from the previous position by the actual telerobot controller.

> Conway et al. offer the following scenario as an example: We perform a complex maneuver with clutches engaged. We then disengage the time clutch to quickly hop over a series of simple manipulation movements, such as pushing a series of switches. A faint "smoketrail" superimposes the forward simulation path over the return video display, helping us to visualize our progress along the chosen path. Having saved some time, we then disengage the position clutch, and by trial and error movements position our manipulator in simulation to begin a complex maneuver. During this phase, the simulation-generated manipulator image moves on the display, but leaves no "smoketrail" of a committed path. Upon reaching the correct position and orientation to begin the next maneuver, we reengage both clutches (the "smoketrail" will now be the new interpolated path segment) and wait for the remote system to catch up. We then begin the next maneuver. In this way we (1) save some time, (ii) use the time saved to later preposition for another action, (iii) avoid taking the actual system through complex, manipulatively unnecessary prepositioning movements, and (iv) do this all in a natural way through simple controls.

Conway et al. tested these ideas experimentally using a Puma robot arm, a joystick hand controller, and a simple two-dimensional positioning task. They compared teleoperation under three conditions: without any predictor display, with predictor display, and with predictor display plus time clutch. Plots of task-completion time as a function of task difficulty ratio (distance moved divided by diameter of target) yielded results for the first two conditions which confirmed the Hashimoto andSheridan [68] results that the predictor by itself made significant improvement (they found up to 50% shorter completion times for some subjects). They also found that adding the time clutch could make further improvement (of up to 40%) if the slewing speed of the robot arm was constrained to be very slow and if the operators used finesse and were careful not to overdrive the system. Various other researchers have adopted versions of the "time clutch." These ideas deserve further development.

Forward-backward editing of commands for prerecorded manipulation

At the extreme of time desynchronization is recording a whole task on a simulator, then sending it to the telerobot for reproduction. This might be workable when one is confident that the simulation matches the reality of the telerobot and its environment, or when small differences would not matter (e.g., in programming telerobots for entertainment). Doing this would certainly make it possible to edit the robot's maneuvers until one was satisfied before committing them to the actual operation. Machida et al. [76] demonstrated such a technique by which commands from a master-slave manipulator could be edited much as one edits material on a video tape recorder or a word processor. Once a continuous sequence of movements had been recorded, it could be played back either forward or in reverse at any time rate. It could be interrupted for overwrite or insert operations. Their experimental system also incorporated computer-based checks for mechanical interference between the robot arm and the environment.

SUPERVISORY CONTROL

The basic idea of supervisory control

The term *supervisory control* is derived from the close analogy between the supervisor's interaction with subordinate human staff members in a human organization and a person's interaction with "intelligent" automated subsystems. A supervisor of humans gives directives that are understood and translated into detailed actions by staff subordinates. In turn, subordinates collect detailed information about results and present it in summary form to the supervisor, who must then infer the state of the system and make decisions for further action. The intelligence of the subordinates determines how involved their supervisor becomes in the process. Automation and semi-intelligent subsystems permit the same sort of interaction to occur between a human supervisor and the computer-mediated process [1][77][78].

In the strictest sense, *supervisory control* means that one or more human operators are intermittently programming and continually receiving information from a computer that itself closes an autonomous control loop through artificial effectors and sensors to the controlled process or task environment. In a less strict sense, *supervisory control* means that one or more human operators are continually programming and receiving information from a computer that interconnects through artificial effectors and sensors to the controlled process or task environment. In both definitions the computer transforms information from human to controlled process and from controlled process to human, but only under the strict definition does the computer necessarily close a control loop that excludes the human, thus making the computer an autonomous controller for some variables at least some of the time.

Figure 23 characterizes supervisory control in relation to the extremes of manual control and full automatic control. Common to the five man-machine system diagrams are displays and controls interfaced with the human operator, and sensors and actuators interacting with a controlled process or environmental task. System 1 represents conventional (i.e., not computer-aided) manual control. In system 2 significant computer transforming or aiding is done in either or both of the sensing and acting (effector) loops. This corresponds to the less strict definition of supervisory control. Note, however, that in both system 1 and system 2, all control decisions depend upon the human operator. If the human stops, control stops.

In the strict forms of supervisory control (systems 3,4), the human operator (supervisor) programs by specifying to the computer goals, objective tradeoffs, physical constraints, models, plans, and "if-then-else" procedures. This specification is usually and most conveniently put in high-level "natural" language — in terms of desired relative changes in the controlled process, rather than in terms of control signals. Once the supervisor turns control over to the computer, the computer

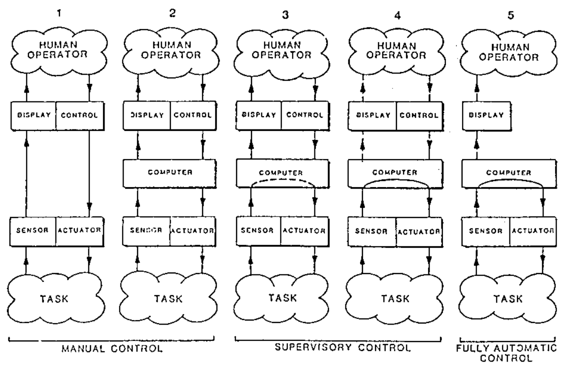

Figure 23. The spectrum of control modes. Broken line indicates minor loops are closed through computer, major loops through human. Solid line indicates major loops are closed through computer, minor loops through human. [From Sheridan, ref. 1]

executes its stored program and acts on new information from its sensors independently of the human, at least for short periods of time. The human may remain as a supervisor, or may from time to time assume direct control (this is called *traded control)*, or may act as supervisor with respect to control of some variables and direct controller with respect to other variables (*shared control).*

Figure 24 illustrates the concept of supervisory control. The human operator provides largely *symbolic* commands (concatenations of typed symbols or specialized key presses) to the computer. However, some fraction of her commands may be *analogic* (hand-control movements isomorphic to the space-time-force continuum of the physical task) in order to point to objects or otherwise demonstrate to the computer relationships that are difficult for the operator to put into symbols. The *local* or *human-interactive computer* (HIC) thus should be human-friendly, able to indicate that it understands the message and able to point out that a specification is incomplete. In this way it should help the operator to edit the message correctly. It also needs to interpret signals from the distant telerobot, storing and processing them to generate meaningful integrated graphic displays. Finally,this local human-interactive computer should contain a knowledge base and a model of the controlled process and task environment and be able to answer queries put to it by the operator. Meanwhile, the subordinate "remote" or *task-interactive computer* (TIC), that accompanies the controlled process must receive commands, translate them into executable strings of code, and perform the execution, closing each control loop though the appropriate actuators and sensors.

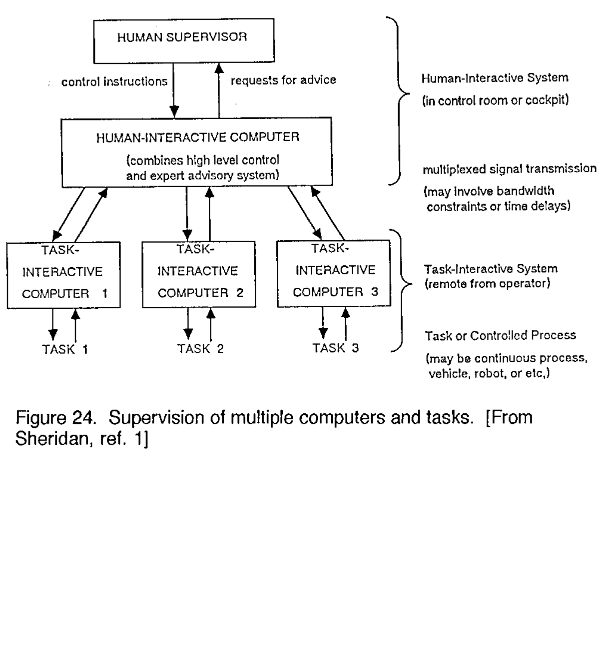

Figure 24. Supervision of multiple computers and tasks. [From Sheridan, ref. 1]

Five generic supervisory functions

The human supervisor's functions are: (l) planning what task to do and how to do it,
(2) teaching (or programming) the computer what was planned;
(3) monitoring the automatic action to make sure all is going as planned and to detect failures; (4) intervening (which means that the supervisor supplements ongoing automatic control activities, takes over control entirely after the desired goal state has been reached satisfactorily, or interrupts the automatic control in emergencies to specify a new goal state and reprogram a new procedure); and (5) learning from experience so as to do better in the future. These are usually time-sequential steps.

Planning

This is the hardest function to model. Formally it means
(1) gaining experience and understanding of the physical process to be controlled, including the constraints set by nature and circumstances surrounding the job,
(2) setting goals that are attainable, or objectives along with tradeoffs, that the computer can "understand" sufficiently well to give proper advice or make control decisions, and
(3) formulating a strategy for going from the initial state to the goal state.

Teaching the computer

The supervisor must translate goals and strategy into detailed instructions to the computer such that it can perform at least some part of the task automatically, at least until the instructions are updated or changed or the human takes over by manual control. This includes knowing the requisite command language sufficiently well that goals and instructions can be communicated to the computer in correct and timely fashion.

Monitoring automatic control

Once the goals and instructions are properly communicated to the computer for automatic execution of that part of the task, the supervisor must observe this performance to ensure that it is done properly, using direct viewing or whatever remote sensing instruments are available. The prompt detection of the presence and location of failures, of conflicts between actions and goals, and the anticipation that either of these is about to occur, are an essential part of the supervisor's job.

Intervening to update instructions or assume direct control

If the computer signals that it has accomplished its assigned part-task, or if it has apparently run into trouble along the way, the human supervisor must step in to update instructions to the computer or to take over control in direct manual fashion, or some combination of the two. Since the controlled process is an ongoing dynamic system, not a machine that can be arbitrarily stopped and started again like a computer, the takeover itself must be smooth so as not to cause instability. Similarly, reverting to the automation must be smooth.

Learning from experience

The supervisor must ensure that appropriate data are recorded and computer-based models are updated so as to characterize current conditions with the most accurate information. Historical data must continuously be analyzed for trends or contingencies leading to abnormalities. All such information must be in a form usable in the future in the four preceding steps.

Manipulating objects and their representations

As mankind has evolved there are two ways in which the human body has affected its environment: by manipulation and by communication. Both can be called "tool using." In manipulation, humans have used their hands, or other parts of the body or mechanical tools in the hands, to apply forces and displacements to physically modify the environment. In communication, the vocal cords or other parts of the body have been used as tools to

make representations for others to observe and understand. As we move toward computer mediation in performing tasks, we necessarily move more toward using our bodies more for communication than for direct manipulation.

The correspondence between human verbal language and digital computer language has been widely appreciated. Both are thought of as alphanumeric strings which have meaning as a function of their syntax and parsability. What seems not to have been so widely appreciated is the close correspondence between human verbal language and human manipulation of objects in the physical environment. This lack of appreciation is all the more surprising since the subject-verb-object sentence (with appropriate modifiers on each) corresponds rather directly to the hand-action-tool "sentence," or more generally the logic of hand/tool-action upon-external object. It has taken the artifact of the teleoperator to make us aware of this close relation. But we still do not have fully satisfactory representational languages for manipulation.

Symbolic and analogic command languages

Teaching or programming a manipulation or mobility task, including specification of a goal state and a procedure for achieving it, and including necessary constraints and criteria, can be formidable or quite easy, depending upon the command hardware and software. By *command hardware* is meant the way in which human motor action — hand, foot, or voice — is converted to physical signals to the computer. Command hardware can be either *analogic* or *symbolic.*

Analogic command means that there is a spatial or temporal isomorphism between human response, semantic meaning, and/or feedback display. For example, moving a control up rapidly to increase the magnitude of a variable quickly, which causes a display indicator to move up quickly, would be a proper analogic correspondence.Pointing to an object to identify it is another example of analogic command. Manual force or position tracking amounts to continuous analogic command.

Symbolic command, by contrast, is accomplished by depressing one or a series of keys (as when typing words on a typewriter), or uttering one or a series of sounds (as in speaking a sentence), each of which has a distinguishable meaning. For symbolic commands, a particular series or concatenation of such responses has a different meaning from other concatenations. Spatial or temporal correspondence to the meaning or the desired result is not requisite. Sometimes analogic and symbolic can be combined, e.g., where up-down keys are both labeled and positioned accordingly.

It is natural for humans to intermix analogic and symbolic commands or even to use them simultaneously. This happens, for example, when one talks and points at the same time, or plays the piano and conducts a choir with one's head.

Alphanumeric symbols could also be used to instruct the telerobot to make a graceful movement, but they might better serve to communicate knowledge-based heuristics for avoiding obstacles or making tactile discriminations (which cannot be done so easily by analogic demonstration). Symbols might be better than analog demonstration for communicating to the telerobot how to draw given geometric figures like squares or triangles, since the figures might end up being more precise. This and naming of objects pointed to would be rule-based. Simply typing a well-learned sequence of letters or numbers would be a skill-based symbolic communication. Table 1 illustrates these relationships.

BEHAVIORAL BASIS	COMMUNICATION CODES CONTINUOUS ANALOGIC	DISCRETE SYMBOLIC
knowledge	play charades	write a computer program
rule	point to a named object	name an object pointed to
skill	draw an O	type an O

Table 1. Examples of symbolic and analogic control at three behavioral levels. [From Sheridan, ref. 1]

Borrowings from industrial robot command language

Early industrial robots could be programmed by means of "teach pendants" (small hand-held switch boxes) by which the teacher, standing adjacent to the robot, could command its joint movements one DOF at a time, thus programming simple routines which could be refined and later replayed many times for assembly-line operations. More sophisticated teach-pendant command structures gradually allowed the teaching of commands for start, stop, speed, etc. between various reference positions, conditional branching conditions, and arbitrarily defined macros [79]. The early robots also had explicit "mid-level" symbolic command languages, such as Ernst's MH-1 [80] and Unimation's PAL and HAL [79,81]. Barber's MANTRAN [82] was an early attempt to build a higher-level language useful for "one-of-a-kind-and-right-now" human-to-telerobot commands. Paul [83] reviews the computational aspects of robot command language.

Brooks' SUPERMAN, and comparison of alternative supervisory teaching modes

T. Brooks [16] developed a high-level command system he called SUPERMAN which allowed the supervisor to use a master arm to identify objects and command elemental motions in terms of those objects. He showed that even without time delay such supervisory control — including both teaching and execution — often took less time and had fewer errors than manual control.

Brooks first developed software to enable the supervisor to teach the computer by performing a manipulation with the master arm of a manipulator and simultaneously code the objects and the movements using a symbolic keyboard. Later, when the human operator required a particular already-trained manipulation, he simply "initialized" a new coordinate system relative to the old one by moving the teleoperator hand to the starting point of the task (e.g., grasping a particular nut or valve handle) and signaling for execution on "this" object. The computer automatically retransformed the old coordinates to a new coordinate system and performed the desired task, possibly also following commands to terminate the execution at a previously identified location or object. Brooks' supervisory programs could, upon certain touch conditions' becoming true, branch into other programs. For example, the telerobot hand could grasp a nut, unscrew it half a turn, pull back to test whether it was off, and, if it was, place it in a (previously located by this demonstration procedure) bucket, or if it was not, repeat the operation.

Six manipulation tasks were identified for experimental investigation: retrieval of a tool from a rack, returning a tool to its rack, taking a nut off, grasping an object and placing it in a container, opening or closing a valve, and digging sand and putting it in a container. In addition, four manual control modes were employed: switch (on-off reverse, or fixed rate), joystick (variable rate), master-slave position control, and master-slave position control with force feedback. Both one-view and two-view (separate displays, not stereo) video conditions were tested. For all these combinations of conditions both direct manual teleoperator and supervisory control were compared.

In all cases the error rates for supervisory control were lower than those for direct manual teleoperation. Theoretically there is no reason why master-slave control with force feedback should be any faster than supervisory control. Consider that the computer could simply mimic the human operator's best trajectory and hence be at least as fast. Unfortunately, in practice there is always a certain overhead associated with retransformation of coordinates, trajectory calculations, and sensor logic. Also, it was generally observed that the subjects were making adaptive motions, whereas the computer was limited to more rigidly defined trajectories and states.

Thus, even with no time delay, supervisory control was found to be more effective (as determined from the task completion times and manipulation errors) than switch rate control, joystick rate control, and master-slave position control. Bilateral force-

reflecting master-slave control was found to be slightly faster than supervisory control but more prone to errors. Since the experiments were performed under "ideal" conditions, it could be predicted in 1979 that supervisory control would show an even greater advantage when used with degraded sensor or control loops (time delays, limited bandwidth, etc.).

Yoerger's experiments on teaching modes

Yoerger [10] extended Brooks' work, developing a more extensive and robust supervisory command system that enabled a variety of arm-hand motions to be defined, called upon, and combined under other commands. In one set of experiments Yoerger compared three different procedures for teaching a robot arm to perform a continuous seam weld along a complex curved workpiece. The end effector (welding tool) had to keep 1 inch away, to retain an orientation perpendicular to the curved surface to be welded, and to move at constant speed.

Part of Yoerger's system was an on-line computer simulation and display that allowed motions of the manipulator to be simulated in all six DOF to test programs before they were actually executed. The operator could view the simulation from any angle, could translate or zoom the display, could run various simulations in faster than real time, and could then call for an actual execution of some already stored trajectory at some specified new location.

Yoerger tested his subjects in three command (teaching) modes using the simulation:

Continuous trajectory analogic demonstration. The human teacher first moved the master (with slave following in master-slave correspondence) relative to the workpiece in the desired trajectory. The computer would memorize the trajectory, and then cause the slave end-effector to repeat the trajectory exactly.

Discrete point analogic specification with machine interpolation. The human teacher moved the master (and the slave) to each of a series of positions, pressing a key to identify each. The human supervisor would then key in additional information specifying the parameters of a curve to be fitted through these points and the speed at which it was to be executed, and the computer would then be called upon for execution.

Analogic specification of reference information and symbolic goal specification relative to the reference. In this mode the supervisor used the master-slave manipulator to contact and trace along the workpiece, to provide the computer with knowledge of the location and orientation of the surfaces to be welded. Then, using the keyboard, the supervisor would specify the positions and orientations of the end effector relative to the workpiece (e.g., to move along but 1 inch away from the designated surface at a given speed and a given angle). The computer could then execute the task instructions relative to the geometric references given.

Figure 25 shows the average results for three experimental subjects, based on running measures of both position error and orientation error in system performance after teaching in each of the three modes. Identifying the geometry of the workpiece analogically, and then giving symbolic instructions relative to it, proved the constant winner. It was further shown that the interface decreased the operator's dependence on visual feedback The system decreased the variability in performance between operators, and the computer graphic display helped the operator understand elements of the programming system without requiring a formal mathematical description of how the commands work.

Yoerger's results showed that analogic teaching can be especially useful when an operator does not know the exact coordinate values of a position but can see via the graphic or television display what he wants. Using analogic definitions in combinatior with symbolic commands simplifies the teaching of telerobotic tasks. Programs can be written in which the operator points (moves) to an object in the task environment and then describes an operation to be done on the object by specifying motions built on the previously defined positions.Using the relative commands, the arm may be moved relative to its current position

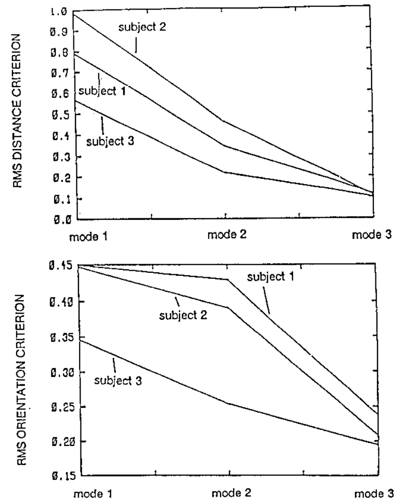

Figure 25. Yoerger's results for alternative methods of teaching. Mode 1, human demonstrated full trajectory, computer reproduced it exactly. Mode 2, human demonstrated series of discrete positions and orientations, computer connected them with smooth trajectory. Mode 3, human indicated relevant surface of workpiece and specified trajectory relative to it with symbolic commands, computer executed as instructed. [From Yoerger, ref. 10]

and orientation. Such relative commands can be useful for describing tool motions, such as turning a valve or brushing a weld.

Mouse-based object level control (S. Schneider and R. Cannon)

Using a planar three-DOF, two-arm manipulation task, Schneider and Cannon [84] demonstrated a computer-graphic supervisory command interface that permitted the operator to move a mouse, click on an object to be moved, drag a "ghost object" to a desired new position, and then release the mouse button. The computer would then dutifully perform the operation. This was essentially similar to Brooks' method for identification by pointing at the object to be grasped and moved and to Yoerger's method of moving a computer-graphics-simulated manipulator to a point in simulated space as a means to specify the subtask goal for subsequent automatic execution.

Schneider and Cannon added two modes. In one the ghost object, when in proximity to a nominal target (say a peg in proximity to a hole), could be made to "snap" into a preprogrammed relation to the target (into the hole). In another mode, again using the mouse, the operator could attach one end of a ghost spring to an arbitrary point on a ghost object and the other end to a fixed point in the environment. The real object, when manipulated, would then assume the equivalent impedance characteristics. In general, equivalent stiffness, damping, and mass can be added in this manner in any independent direction.

D. Cannon's experiments with "put that there"

D. Cannon [85] conducted experiments in analogic task teaching in unstructured environments wherein the supervisor's role was limited to task conception and pointing, and the telerobot did the rest. (The phrase "put that there" was originally popularized by Bolt [86] as a graphics interface technique.) Using a mobile robot with a six-DOF arm and two pan-tilt CCD video cameras mounted on a post (Figure 26), the human operator aimed camera reticles at the crucial objects and destinations to accomplish a real-world task. From camera angle triangulations, in concert with combinations of meaningful subphrases such as "put that...and that...there," the telerobot interactively built arm and mobile base trajectories for the immediate or delayed execution of tasks. The

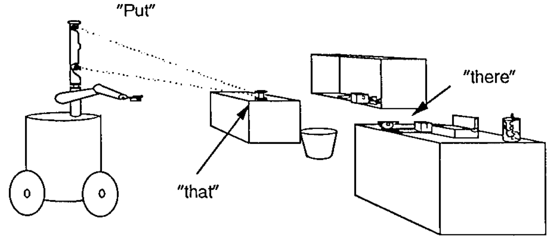

Figure 26. Cannon's ranging telerobot for "put-that-there" experiments. [Courtesy of D. Cannon.]

tasks involved objects and locations about which the robot had essentially no foreknowledge, such as putting tools in a tool box. items of trash in a wastebasket, and blocks on a pallet; all the items had been strewn randomly in a workspace. Cannon demonstrated that his technique reduced human supervisory control time and sped up task-execution time.

Such point-and-select and "ghost object manipulation" methods are a bridge between autonomous robotics and telemanipulation. Though point-and-select telerobots with autograsping and obstacle-avoidance systems can often operate in unstructured environments without any telemanipulation, a supervisor may be in a stronger position if he has hand/gripper telemanipulation and perhaps full robot telemanipulation (up to the number of DOF controllable) at times during or at the ends of some trajectories. Indeed, an operator may benefit from having a full set of options across the entire spectrum from autonomy to telemanipulation and using a point-and-select interface of some type to connect the two ends of the continuum. Perhaps this powerful combination can be achieved with very little overhead if the hardware and the software are chosen appropriately.

In cases involving significant time delays, the point-and-select approach eliminates the need for the move-and-wait stepping actions of telemanipulation. This is because destinations, rather than incremental motions, are prescribed so that the robot can move quickly and continuously between locations of importance. Task-specific criteria, such as proper welding speed and offset requirements, could be incorporated such that the phrase "weld from there to there" creates a routine that installs a welding rod and then, using proximity sensors, follows the contours of any curved surface between the two points while keeping the angle and the spacing of the rod correct for welding on that surface. The command "paint all but that" could become meaningful with advanced natural language systems. In all such cases, the role of the human remains at the highest level of supervisory control commensurate with defining tasks involving objects and destinations about which the robot has no specific foreknowledge.

Dual-mode sensory-based teaching (Hirzinger and Heindl)

Hirzinger and Heindl [87] and Hirzinger and Landzettel [88] proposed and experimentally implemented a technique by which the human operator, either on or off line, could continuously specify a position trajectory to a telerobot in space, using an isometric "force-joystick" or "sensor ball" to control rate in six axes. Especially in cases where there was time delay, a local computer simulation or duplicate hardware teleoperator could be used to produce immediate and easily observable feedback. When the telerobot sensed contact with the environment, or alternatively when the operator chose, there was a switch to a force control mode, where the forces applied to the six axes of the sensor ball served as reference signals to a force a control loop closed locally at the remote teleoperator.

The former (rate) mode presumably would be used in free space, and the latter (force) mode when contact with external objects threatens instability and/or the operator needs force feedback (e.g., in fitting a peg in a hole). Note that Hirzinger's system was not true force feedback. The spring restoring forces from the six-axis joystick were what was felt by the operator, and these were also giving reference signals to the local force control loops. Ranging sensors attached to the end effector could be made to act as pseudo-force sensors in contributing to the balance of end-effector forces to commanded forces.

Asada-Yang techniques for teaching force-position-time relations by demonstration

Asada and colleagues have experimented with a variety of methods for teaching by demonstrating. Asada and Yang [89] demonstrated a system to capture the deburring skill of an experienced machinist and transfer that skill to a robot. The machinist taught the computer by repeated demonstrations, and at the same time a variety of sensor signals were recorded, such as forces, positions, grinding-wheel speed and torque, and sounds. Analysis of these data by means of discriminant functions determined an "average" mapping or control law from process state variables (inputs to the human) into control actions (human outputs).

The teaching process consisted of
(1) predetermining what single "feature" characterizes the data as read by each of the L sensors,
(2) transforming the data from each teaching run for each action A_i of N such control actions into a vector $\mathbf{x}$ in "feature space" whose elements are feature weightings,
(3) normalizing each axis of feature space by the standard deviation of all N blocks of data (one for each of N actions), and
(4) computing the mean and the standard deviation in feature space of all the vectors corresponding to each A_i.
The class w_i was then defined by a hypersphere in feature space centered on that mean and having a radius equal to that standard deviation. Later, when running the program, whatever $\mathbf{x}'$ occurred was then compared with all N hyperspheres in feature space, and the action A_i corresponding to the closest one (by mean square distance) was triggered. Asada and Liu (1990) proposed similar teaching by means of neural-net conditioning.

Funda's scheme for recoding operator actions into commands by class recognition

Funda et al. [90 developed a system wherein the operator programs by kinesthetic as well as visual interactions with a (virtual) computer simulation. The instructions to be communicated to the actual telerobot are generated automatically in a more compact form than record and playback of analog signals. Several free-space motions and several contact, sliding and pivoting motions, which constitute the terms of the language, are generated by automatic parsing and interpreting of kinesthetic command strings relative to the model. These are then sent on as instruction packets to the remote slave. The Funda et al. technique also provides for error handling. When errors in execution are detected at the slave site (e.g., because of operator error, discrepancies between the model and real situation and/or the coarseness of command reticulation), information is sent back to help update the simulation. This is to represent the error condition to the operator and allow him to more easily see and feel what to do to correct the situation.

Action, direction, agreement, negation, and delegation as bases for command

T. Brooks [91] reports on experiments with five progressively graded levels of human supervisory control of a telerobotic vehicle, which he calls *action, direction, agreement, negation,* and *delegation.* By *action* he means either real-time direct and continuous control by the operator or continuous record and then playback. In either case the operator must "do" each and every step of the task. *Direction* means that the operator specifies each in a series of small incremental goals, and the computer interprets and executes these one step at a time. *Agreement* means that the computer selects an action but waits for the operator to agree to it;

if he doesn't, another action can be selected, and so on. *Negation* means that the computer seeks to carry out a task autonomously but the human operator may override it. *Delegation* means that the human operator specifies overall goals, then turns over part or all of a task to the computer to perform as it sees fit. The computer in this case has no responsibility to inform the operator what it decides. At the time of this writing the implementation had not been completed.

Communication confirmation in command and display

It is easy to think that communication with a machine requires only giving action commands and getting back indications of state, where both command and state information are coded symbolically, analogically, or in combination. Indeed, that has been characteristic of most machines, from dishwashers to automobiles to aircraft. However, reflection on how humans communicate with one another reveals that something more is going on, something very important: there is intermediate feedback for both giving commands and getting state information, as shown in Figure 27. If an assignment is given to an unsophisticated subordinate he may simply go off and act as best he understands, much as a simple machine would. A more sophisticated human worker (or an intelligent machine) would respond at that point with something like "This is what I understand you have asked me to do; is that correct?", leaving the supervisor the opportunity to clarify, and not have to guess whether the subordinate has understood. Similarly, when one person reports on the state of objects or events, the intelligent listener is likely to nod or otherwise indicate what he understands, or to ask for clarification. The human supervisor of an intelligent machine should be given the opportunity to do the same, with the machine then confirming, clarifying, or providing more detail as necessary. This is the essence of human dialog, and it should be built into supervisory control systems.

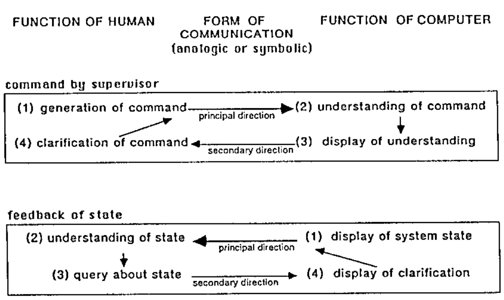

Figure 27. Intermediate feedback in command and display. Heavy arrows indicate the conventional understanding of functions. Light arrows indicate critical additional functions which tend to be neglected. [From Sheridan, ref. 1]

Voice command

Voice-recognition systems (for voice command by human operators) are now widely available at reasonable prices. They all must be trained by one or more speakers on a limited vocabulary. Naturally there are tradeoffs involving size of vocabulary, speaker training, speaking speed and style, number of different speakers to be accommodated by the same algorithm (one speaker is always preferred), recognition reliability, and cost. If speech consists of disconnected words, recognition is much more straightforward than if words are connected as in natural speech. Further, a single speaker will modify the sound of his or her voice as a function of stress, fatigue, and attention.

Speech-recognition algorithms are of various sorts, ranging from rule-based techniques and template matching more probabilistic or self-learning approaches such as hidden Markov modeling and neural networks. Probabilistic algorithms generally store contingent probabilities based on the two previous words spoken. Measures of the vocabulary such as *perplexity*, defined as $2^{(\mathrm{entropy})}$, or an equivalent number of equally likely events to be distinguished, are commonly used.

It is important that the designer of speech command formats consider not only speech-recognition reliability and speed, but also the acceptability and naturalness of use by the speaker. For example, moving a cursor by using the speech commands "Up, up, up, left, left" would be easy enough for the computer but time-consuming for the operator, whereas "Go to the top right corner of the rectangle" should be understandable by the computer and much more natural for the operator.

Voice command for teleoperation has been experimented with for at least a decade [92], but thus far its acceptance has been limited.

Computer-graphic aids for avoiding obstacles

Park [93] developed a computer-graphic control aid by which a supervisor could plan and essentially try out an anticipated telerobot arm movement in a simulation, again before committing to the actual move. He assumed that for some obstacles the positions and orientations were already known and represented in a computer model. The user commanded each straight-line move to a subgoal point in three-space by designating a point on the floor or the lowest horizontal surface (such as a table top) by moving a cursor to that point (say A in figure 28a) and clicking, then lifting the cursor by an amount corresponding to the desired height of the subgoal point (say A) above that floor point and observing on the graphic model a blue vertical line being generated from the floor point to the subgoal point in space. This process was repeated for successive subgoal points (say B and C). The user could view the resulting trajectory model (figure 28b) from any desired perspective (though the "real" environment could be viewed only from the perspective provided by the video camera's location).

Either of two collision-avoidance algorithms could be invoked: a detection algorithm which indicted where on some object a collision occurred as the arm was moved from one point to another, or an automatic avoidance algorithm which found (and drew on the computer screen) a minimum-length no-collision trajectory from the starting point to the new subgoal point. Park's aiding scheme also allowed new observed objects to be added to the model by graphically "flying" them into geometric correspondence with the model display. Another aid was to generate "virtual objects" for any portion of the environment in the umbral region (not visible) after two video views (figure 28c). In this case the virtual objects were treated in the same way in the model and in the collision-avoidance algorithms as the visible objects. Experiments with this technique showed that it was easy to use and that it improved safety greatly.

Chiruvolu [94] experimented with the idea of superposing on the video model-based images allowing the operator to "see through" the teleoperator arm and hand. This allows for peg-in-hole or other assembly operations which otherwise are not possible with limited camera views.

COGNITION AND MENTAL MODELS

Mental models in relation to other "internal" models in teleoperator systems

Before elaborating on the relation of mental models and decision aids to the plan-teach-monitor-intervene-learn functions, it is important to consider what other kinds of models are embodied within a supervisory control system, and where, physically, these are located. Figure 29 shows four loci of models in a telerobot system: (1) mental models (presumably resident in the supervisor's head), (2) software-based models in the computer,

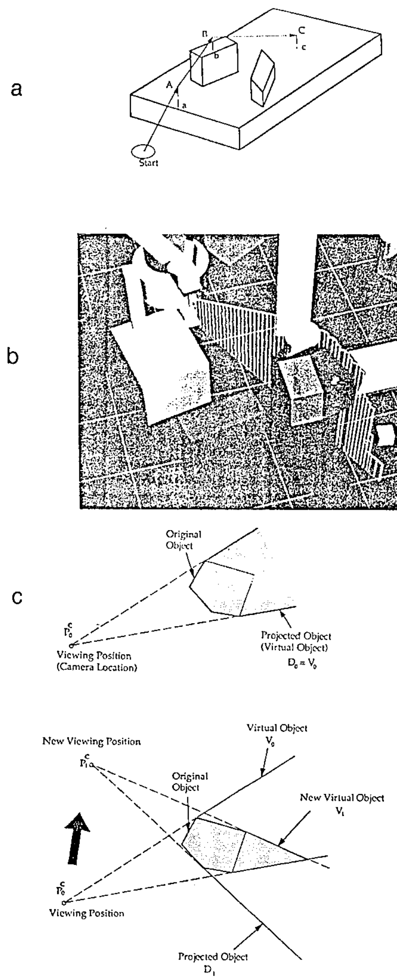

Figure 28. Park's display of computer aid for obstacle avoidance. a, human specification of subgoal points on graphic model; b, computer display of composite planned trajectory with lines to floor to indicate heights; c, generation of virtual obstacles for single viewing position (above) and pair of viewing positions (below). [From Park, ref. 93]]

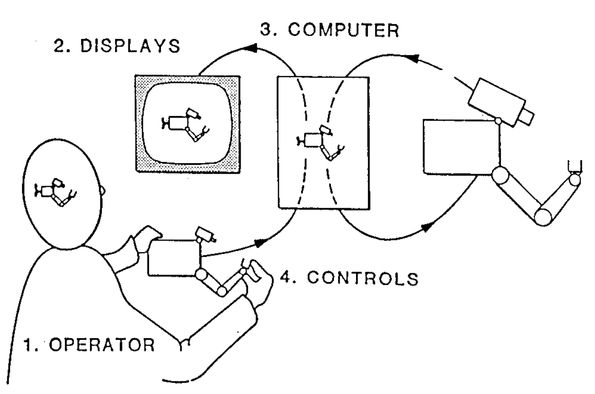

Figure 29. Four loci of models in the supervisory control system: (1) mental model; (2) display representation; (3) control configuration; (4) computer model. [Courtesy of W. Verplank.]

(3) representations of the telerobot-task in the configuration of the human's hand controls, and (4) representations of the telerobot-task in the graphics-text presentation on the supervisor's displays (including computer-generated, video, and other-than-visual displays). The latter two are not typically considered models, but they truly are. The arrangement of what the operator sees and what he does with her hands and how this corresponds with what he thinks is critical. Miscorrespondence (inability or difficulty in mapping from eye or other sensor to mind, and then to hand) is likely to cause delays and errors. The computer's internal models will run at their own speed and in terms of whatever the programmer decided, but these must bear correspondence to the mental and display-control models. All, of course, must correspond to the external reality. Designing in this correspondence is not a trivial matter. In the parlance of conventional human factors, notions of *display-control compatibility, user expectation stereotypes, naturalness,* and *transparency* are often used.

Some modeling challenges

Modeling the human versus modeling the human-machine combination

One of the most interesting modeling questions is "What is modeled?". The kinematics and dynamics of mechanical machines, and the transfer functions and logical mappings of electronic systems of a teleoperator or telerobot, may be modeled in usual ways. When the human operator is included, however, there is a challenging problem. It has been shown [26] in simple manual control systems that the best-fit (in a least-squares sense) dynamic model of human input-output characteristics changes dramatically as a function of the controlled process. In fact, within a range of controlled processes within which the human operator can sucessfully maintain control, the human tends to adopt the inverse dynamics of the controlled process, such as to keep the open loop characteristic of human-plus-controlled-process constant [26] and in a form as close as possible to optimal within the fixed neuromuscular and neural processing constrains of the human.

There is every reason to believe that humans attempt to do the same for more complex systems, yet our understanding of this seeming invariant property of human-machine systems remains poorly tested or understood beyond the most simple linear control loops [1].

Describing system performance

How to describe in an objective way the performance of human and teleoperator in performance of tasks? We have available neither the descriptive language nor the theory to do the task properly. We need a language to describe the repositioning in time and space and force of the salient elements of the teleoperator and the objects in the environment in interaction. Continuous trajectories in a space of 6 (DOF) times the number of independent elements in the teleoperator plus environment would descrive everything, but this clearly is infeasible. Some more compact description is obviously preferable. For example, a musical score describes what a symphony orchestra does in a way which is more or less repeatable. There are even ways of scoring dance. Yet currently we have no acceptable way of "scoring" a telemanipulation task.

Modeling direct and supervisory human control

By direct control we mean the human takes what is given (observed by him or her) and directly (continuously of intermittently) operates controls which cause movements of the teleoperator in one-to-one mapping. Master-slave position control, joy-stick rate control, and switch-operated control for each degree of freedom are examples. A model of human control in this case can be made by equations, by an input-output table, by a state-directed graph, etc.

Modeling supervisory control is different, and mush more difficult. The off-line and heavily mental events of planning,

teaching, monitoring, intervening and learning are in stark contrast to sensory-motor skill, and are sufficiently decoupled from the instantanous phyical movements of the teleoperator mechanism that the above forms of model are inadequate. Furthermore the very essence of supervision is that that human is proactive rather than reactive, determining what task is to be done, and how it is to be done. In fact, one must attribute to the human supervisor some measure of free will (which normally does not come up in characterizing the task of a subordinate worker). Free will, by no defnition is easy to model. Furthermore, assuming the supervisor is using some form(s) of decision-aiding, there is the question of whether the human is slavishly folowing the decision aid, or whether the human is thinking and deciding independedntly of the decision aid. Of course, if it is the human-plus-computer in tandem that one is modeling (as per the discussion above) then a model may not have to discriminate between human and computer. Finally, one can assert that modeling the human supervisor is exacerbated by the sheer complexity of the kinds of systems likely to be encountered.

Modeling mental state: subjective workload and sense of presence

Until recent years no one much worried about mental states of the human operator which might relate to performance. Nothing seemed to count but the performance of the system, and operators were selected and trained and given the displays and controls to enable them to do the best job possible, quite apart from how they felt subjectively. Gradually however, it became clear that mental state affects physical performance, and if one could measure and predict mental state, then perhaps one could predict performance.

Mental state is not directly and physically measurable, and historically some psychologists (traditionally the "behaviorists") have asserted that even attampts to infer mental state are fruitless. However, there is much current interest in mental state, and there are several examples of the attributes of mental state in which there is currently keen interest.

One of these is mental workload. The idea is that if mental workload is excessive, it is a precusor to a sudden and catastrophic decrement in human performance, though by measuring performance directly one cannot usually anticipate that performance is about to drop off. Mental workload has been measured [96] for airline pilots and nuclear power plant operators, and it is appropriate to measure it for human operators of teleoperators performing prolonged activities in hazardous waste removal, radioactive or chemically toxic laboratory tasks, etc.

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Bibliography

This bibliography has been prepared by the NASA Center for AeroSpace Information (CASI)[1], to support the Lecture Series 193: 'Advanced Guidance and Control Aspects in Robotics.' It includes selected reports, papers, books, and other items entered in the NASA STI Database from 1993 through early 1994.

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Intelligent robots and computer vision XII: Algorithms and techniques; Proceedings of the Meeting, Boston, MA, Sept. 7-9, 1993
94A12322
CASASENT, DAVID P. (Carnegie Mellon Univ., Pittsburgh, PA) Bellingham, WA, Society of Photo-Optical Instrumentation Engineers (SPIE Proceedings. Vol. 2055), 1993, 645 p. (For individual items see A94-12323 to A94-12325)
Topics discussed in this volume include pattern recognition in computer vision; computer vision; sampling and coding in computer vision; image processing; morphological, wavelet, and Gabor processing; and neural nets and fuzzy logic in machine vision. Papers are presented on real-time model-based vision for industrial domains, a vision system based on a classification connectionist algorithm, finding landmark features under a broad range of lighting conditions, a high-speed low-latency portable visual-sensing system, image analysis of photochromic ink for securing applications, and image coding and image activity measurement. Attention is also given to the acquisition of range images in an integrated vision system environment, a robust line extraction and matching algorithm, a new entropy operator for edge abstraction, wavelet image representation and applications in computer vision, morphological granulometric shape recognition in noise, adaptation of Gabor filters for simulation of human preattentive mechanism for a mobile robot, a general learning scheme for robot coordinate transformations using dynamic neural network, and the design and implementation of a fuzzy logic yaw controller.

Sensorbased space robotics - ROTEX and its telerobotic features
94A11283
HIRZINGER, G.; LANDZETTEL, K.; DIETRICH, J. (DLR, Oberpfaffenhofen, Germany) IAF, International Astronautical Congress, 44th, Graz, Austria, Oct. 16-22, 1993. 21 p.
In early 1993, the space robot technology experiment ROTEX has flown with Space Shuttle COLUMBIA (Spacelab mission D2 on flight STS-55 from April 26 to May 6). A multisensory robot on board the spacecraft successfully worked in autonomous modes, teleoperated by astronauts, as well as in different telerobotic ground-control modes. These include on-line teleoperation and telesensor programming, a task-level oriented programming technique involving 'learning by showing' concepts in a virtual environment. The robot's key features are its multisensory gripper and the local sensory feedback schemes, which are the basis for shared autonomy. The corresponding man-machine interface concepts using a 6 DOF nonforce-reflecting control ball and visual feedback to the human operator are explained. Stereographic simulation on-ground was used to predict the robot's free motion and the sensor-based path refinement on board; prototype tasks performed by this space robot were the assembly of a truss structure, connecting/disconnecting an electrical plug (orbit replaceable unit exchange), and grasping free-floating objects.

On the nonlinear dynamics of a space platform based mobile flexible manipulator
94A11110
MODI, V. J.; MAH, H. W.; MISRA, A. K. (British Columbia Univ., Vancouver, Canada); (McGill Univ., Montreal, Canada) IAF, International Astronautical Congress, 44th, Graz, Austria, Oct. 16-22, 1993. 22 p. Research supported by Centers of Excellence Program.
A relatively general formulation is developed for studying the dynamics of an orbiting arbitrary chain of translating, slewing flexible bodies. The formulation accounts for transverse, axial, and torsional deformation of beams. The model takes into account joint flexibility in three dimensions as well as specified and generalized coordinates at the joints, with freedom to transverse over a flexible platform free to librate and carrying a flexible payload. The model can also analyze a cluster of flexible bodies at joints forming 'flower petal-type' configurations, rigid central-body-based geometry applicable to a large class of scientific and communications satellites. The versatility of the formulation permits dynamical analysis and nonlinear control of a wide class of space- and ground-based manipulators.

Optimal trajectories for a manipulator on a satellite by the method of dynamic programming (DP)
93A56261
YAMAGUCHI, ISAO; KIDA, TAKASHI; UENO, SEIYA; TANAKA, MASAKI (National Aerospace Lab., Chofu, Japan); (Yokohama National Univ., Japan); (Toshiba Corp., Kawasaki, Japan) In: Space Sciences and Technology Conference, 35th, Nagaoka, Japan, Oct. 28-31, 1991, Proceedings (A93-56251 24-12). Tokyo, Japan Society for Astronautical and Space Sciences, 1991, p. 29, 30.
This paper discusses the optimal trajectories generation for a space robot manipulator by the method of dynamic programming (DP). The results of numerical examples in which the attitude error for the two-dimensional model with a two-joint arm is minimized are in good agreement with the analytical solutions.

Skill compensation and dynamic coupling of macro/smart effector system
93A56260
MACHIDA, KAZUO; TODA, YOSHITSUGU; IWATA, TOSHIAKI (Electrotechnical Lab., Tsukuba, Japan) In: Space Sciences and Technology Conference, 35th, Nagaoka, Japan, Oct. 28-31, 1991, Proceedings (A93-56251 24-12). Tokyo, Japan Society for Astronautical and Space Sciences, 1991, p. 25, 26.
A smart end effector was developed to add dexterous and flexible capability to a long space manipulator arm. It provides fine adjustment for precise error compensation and delicate force control by a remote-end sensor feedback. The performance of the

skill compensation and the dynamic coupling problem between the long arm and the smart end effector are examined.

Control of a spacerobot at the time of capturing a target
93A56259
YAMADA, KATSUHIKO; YOSHIKAWA, SHOJI; KOYAMA, HIROSHI (Mitsubishi Electric Corp., Amagasaki, Japan) In: Space Sciences and Technology Conference, 35th, Nagaoka, Japan, Oct. 28-31, 1991, Proceedings (A93-56251 24-12). Tokyo, Japan Society for Astronautical and Space Sciences, 1991, p. 21-24.
When a spacerobot captures a target, impact forces exert on the hand and on the target. We studied the relation between the velocity of the hand to the target and the magnitude of the impact forces. The magnitude can be estimated by the eigenvalues of the inverse inertia matrix of the spacerobot and the target.

On the capture control for space robot
93A56257
FUJII, HIRONORI; MURAYAMA, TSUTOMU (Tokyo Metropolitan Inst. of Technology, Japan) In: Space Sciences and Technology Conference, 35th, Nagaoka, Japan, Oct. 28-31, 1991, Proceedings (A93-56251 24-12). Tokyo, Japan Society for Astronautical and Space Sciences, 1991, p. 17, 18.
A capture control is studied in application for space robot technology. The acceleration control is one of the widely used methods for this kind of problem. In that control law, the feedback gains for position and velocity are set to be constant with respect to the time. In the present study, the feedback gains are treated as functions of state variables and time, and thus the responses of the system can be shaped more freely. The controlled system is also assured its stability in the sense of Liapunov.

Research of a free-flying telerobot. V - Handling a target with multi-arms
93A56255
TODA, YOSHITUGU; IWATA, TOSHIAKI; MACHIDA, KAZUO; ASAKURA, MAKOTO; FUKUDA, YASUSI; OOTUKA, AKIKO (Electrotechnical Lab., Tsukuba, Japan); (Toshiba Corp., Kawasaki, Japan) In: Space Sciences and Technology Conference, 35th, Nagaoka, Japan, Oct. 28-31, 1991, Proceedings (A93-56251 24-12). Tokyo, Japan Society for Astronautical and Space Sciences, 1991, p. 11, 12.
This report presents manipulation and handling topics of an ongoing program for a research and development of a free-flying telerobot for space use. A developed ground experiment model has two manipulators and a capturing mechanism. A sensory feed back control method enables impedance and active limp control of manipulators. We conclude that these control methods are effective when the telerobot catches a target with a manipulator, moves with a manipulator or manipulators, transfers one manipulator to another, or transfers manipulators to a capturing mechanism.

Development of an autonomous satellite robot for retrieving a satellite
93A56253
KOMATSU, TADASHI; UENOHARA, MICHIHIRO; IIKURA, SHOICHI; MIURA, HIROFUMI; SHIMOYAMA, ISAO (Toshiba Corp., Kawasaki, Japan); (Tokyo Univ., Japan) In: Space Sciences and Technology Conference, 35th, Nagaoka, Japan, Oct. 28-31, 1991, Proceedings (A93-56251 24-12). Tokyo, Japan Society for Astronautical and Space Sciences, 1991, p. 7, 8.
We developed a two-dimensional operation test-bed of an autonomous free-flying space robot for retrieving a satellite. This robot is floating on a planar base using air bearings and is able to fly around using thrusters for position control and a control moment gyro for attitude control. This robot also installs hardware systems such as vision systems, board computers, image processing units, and software systems such as algorithms for path plannings.

Remote surface inspection system
93A55469
HAYATI, SAMAD; BALARAM, J.; SERAJI, HOMAYOUN; KIM, WON S.; TSO, KAM S. (JPL, Pasadena, CA); (SoHar Corp., Beverly Hills, CA) Robotics and Autonomous Systems (ISSN 0921-8890), vol. 11, no. 1, May 1993, p. 45-59. (Previously announced in STAR as N93-32099)
This paper reports on an on-going research and development effort in remote surface inspection of space platforms such as the Space Station Freedom (SSF). It describes the space environment and identifies the types of damage for which to search. This paper provides an overview of the Remote Surface Inspection System that was developed to conduct proof-of-concept demonstrations and to perform experiments in a laboratory environment. Specifically, the paper describes three technology areas: (1) manipulator control for sensor placement; (2) automated non-contact inspection to detect and classify flaws; and (3) an operator interface to command the system interactively and receive raw or processed sensor data. Initial findings for the automated and human visual inspection tests are reported.

A controller design framework for telerobotic systems
93A54269
KAZEROONI, H.; TSAY, TSING-IUAN; HOLLERBACH, KARIN (California Univ., Berkeley); (National Cheng Kung Univ., Tainan, Taiwan); (California Univ., Berkeley and San Francisco) IEEE Transactions on Control Systems Technology (ISSN 1063-6536), vol. 1, no. 1, March 1993, p. 50-62.
This paper presents a framework for designing a telerobotic system controller. This controller is designed so the dynamic behaviors of the master robot and the slave robot are functions of each other. This

paper first describes these functions, which the designer chooses based upon the application, and then proposes a control architecture to achieve these functions. To guarantee that the specified functions and proposed architecture govern the system behavior, H(infinity) control theory and model reduction techniques are used. Several experiments were conducted to verify the theoretical derivations. This control method is unique, because it does not require any transfer of either position or velocity information between the master robot and the slave robot; it only requires the transfer of forces. Although this property leads to a wider communication bandwidth between the master and slave robots, the entire system may still suffer from a positional error buildup between the master robot and slave robot.

Data integration in multi-sensor based robotic workstations
93A54229
CHEN, QIN; LUH, J. Y. S. (Clemson Univ., SC) In: IEEE International Conference on Systems Engineering, Kobe, Japan, Sept. 17-19, 1992, Proceedings (A93-54226 23-66). New York, Institute of Electrical and Electronics Engineers, Inc., 1992, p. 131-134. Research supported by Clemson Univ..
A relaxation labeling algorithm is developed. The major advantage of this algorithm over the existing ones is that the mathematic operation is simplified. The simplification eases the analysis of the convergence properties. Both the theoretical and application aspects of the proposed algorithm are investigated. The local convergence properties of a labeling process with n labels and m labels are established. The investigation of the interaction among the nodes in a multinode labeling process reveals some insight into the mathematical issues involved in the relaxation operations.

Intelligent sensing and control for advanced teleoperation
93A54158
LEE, SUKHAN (JPL, Pasadena; Southern California Univ., Los Angeles, CA) IEEE Control Systems Magazine (ISSN 0272-1708), vol. 13, no. 3, June 1993, p. 19-28.
A theoretical framework is presented for a 'sensing-knowledge command-fusion' paradigm of interactive and cooperative sensing and control in advanced teleoperators, which takes advantage of both current and projected robotic dexterousness and sensor-based autonomy capabilities. Attention is given to (1) a method for the achievement of a sensing-knowledge-command computational mechanism that implements the intended cooperative/ interactive system, and (2) the system architecture and man/machine-interface protocols entailed by this implementation.

Experimental object-level strategic control with cooperating manipulators
93A53196
SCHNEIDER, STANLEY A.; CANNON, ROBERT H., JR. (Stanford Univ., CA) International Journal of Robotics Research (ISSN 0278-3649), vol. 12, no. 4, Aug. 1993, p. 338-350.
This article presents the high-level control module and user interface of the Dynamic and Strategic Control of Cooperating Manipulators (DASCCOM) project at Stanford University's Aerospace Robotics Laboratory. In addition to cooperative dynamic control, DASCCOM incorporates real-time visionased feedback, a novel strategic programming technique, and an iconic 'object-only' graphical user interface. By focusing on the vertical integration problem, we are examining not only these subsystems, but also their interfaces and interactions. The control system implements a multilevel hierarchical structure interconnected via a real-time network. At the highest level, a mouse-driven graphical user interface allows an operator to direct the activities of the system conceptually. Strategic command is provided by an event-driven finite state machine. This methodology provides a powerful yet flexible technique for managing concurrent system interactions. The dynamic controller implements object impedance control - an extension of Neville Hogan's impedance control concept to cooperative multiple-arm manipulation of a single object. This article concentrates on user interfacing techniques and strategic programming capabilities. These modules allow the user to directly specify conceptual object relationships. Experimental results are presented, showing the system locating and identifying a moving object, 'catching' it, and performing a simple cooperative assembly. Each of these operations is executed autonomously, with only object-level task-specification direction from a remote operator.

Mobile robots VI; Proceedings of the Meeting, Boston, MA, Nov. 14, 15, 1991
93A53170
WOLFE, WILLIAM J.; CHUN, WENDELL H. (Colorado Univ., Denver) ; (Martin Marietta Corp., Denver, CO) Bellingham, WA, Society of Photo-Optical Instrumentation Engineers (SPIE Proceedings. Vol. 1613), 1992, 378 p. (For individual items see A93-53171 to A93-53173)
Various papers on mobile robots are presented. Individual topics addressed include: high-level modes for controlling mobile robots, controlling a mobile robot using partial representations, batlike mobile robot for tracking a moving obstacle, self-awareness in mobile robots, autonomous vehicle maneuvering, survival of falling robots, junction detection and pathway selection, robot path planning based on variational methods, mobile robot localization with multiple stationary cameras, robot path planning using expert systems and machine vision, robot mapping in unstructured environments. Also discussed are: model for shape and motion perception, vision-based method for autonomous landing, multilayer robust estimation for motion segmentation, robot position estimation using range and compass data, space-time tradeoffs for adaptive

real-time tracking, new vision-based approach to navigation, vision algorithm for mobile vehicle navigation, thermal and range fusion for a planetary rover.

Joint-space Lyapunov-based direct adaptive control of a kinematically redundant telerobot manipulator
93A53038
NGUYEN, CHARLES C.; ZHOU, ZHEN-LEI; MOSIER, GARY E. (Catholic Univ. of America, Washington); (NASA, Goddard Space Flight Center, Greenbelt, MD) Control and Computers (ISSN 0315-8934), vol. 21, no. 1, 1993, p. 23-27.
This paper presents the design of a joint-space adaptive control scheme for controlling the slave arm motion of a dual-arm telerobot system developed at Goddard Space Flight Center (GSFC) to study telerobotic operations in space. Each slave arm of the dual-arm system is a kinematically redundant manipulator with seven degrees of freedom (DOF). Using the concept of model reference adaptive control (MRAC) and Liupunov direct method, we derive an adaptation algorithm that adjusts the PD controller gains of the control scheme. The development of the adaptive control scheme assumes that the slave arm motion is non-compliant and slowly varying. The implementation of the derived control scheme does not require the computation of manipulator dynamics which makes the control scheme sufficiently fast for real-time applications. Computer simulation study performed for the 7-DOF slave arm shows that the developed control scheme can efficiently adapt to sudden change in payload while tracking various test trajectories such as ramp or sinusoids with negligible position errors.

Computer vision for autonomous robotics in space
93A53031
WONG, A. K. C. (Waterloo Univ., Canada) In: Visual information processing II; Proceedings of the Meeting, Orlando, FL, Apr. 14-16, 1993 (A93-53022 23-63). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1993, p. 176-191. Research supported by Manufacturing Research Corp. of Ontario, Thomson-CSF, Spar Aerospace, Ltd., et al.
A robust robot vision system is presented and its real-time capability for carrying out vision tasks is presented. The system can synthesize a wire-frame model of a 3D object from a sequence of images if the camera position relative to each of the images is approximately known. Hence such a task can be achieved from images taken by a camera mounted on a robot arm. Once the model is obtained, a rule-network for scene interpretation based on a hypothesis refinement procedure can be constructed and used to recognize, locate, and track the object. A variety of experiments are used to show that such a capability has a number of applications in the space robot project.

Motion planning of a dual-arm free-floating manipulator with inertially fixed base
93A51450
AGRAWAL, SUNIL K.; SHIRUMALLA, SHRAVAN (Ohio Univ., Athens) In: AIAA Guidance, Navigation and Control Conference, Monterey, CA, Aug. 9-11, 1993, Technical Papers. Pt. 3 (A93-51301 22-63). Washington, American Institute of Aeronautics and Astronautics, 1993, p. 1472-1481. Research supported by NSF.
A scheme for joint and Cartesian motion planning of a dual arm free-floating planar roots is presented using position and rate kinematic equations so that the base of the robot remains inertially fixed. Even though free-floating manipulators are characterized by nonholonomic constraints, it is shown that the inverse position kinematics coupled with an iterative search procedure results in identical path predicted by direct integration of the rate equations. It is shown that singularities can be easily avoided.

Adaptive spline networks for estimating camera control parameters in robot-vision system
93A50760
LAYNE, J. D. (Martin Marietta Astronautics Group, Denver, CO) In: WNN 92; Proceedings of the 3rd Workshop on Neural Networks: Academic/Industrial/NASDefense, Auburn Univ., AL, Feb. 10-12, 1992 and South Shore Harbour, TX, Nov. 4-6, 1992 (A93-50726 21-63). San Diego, CBellingham, WA, Society for Computer Simulation/Society of Photo-Optical Instrumentation Engineers, 1993, p. 349-354.
Image centroids are frequently used to accurately locate features in images in many computer vision problems. However, non-linear effects in the projection of object features to the image plane can cause significant errors in the centroids, and hence errors in pose estimation and camera calibration. This paper describes a neural network that predicts centroid errors due to surface tilt and lens distortion. The approach is based on multivariable function approximation. Backpropagation networks trained too slowly and generalized poorly at estimating the camera control parameters, hence an adaptive spline network (MARS) was implemented that meets accuracy and performance requirements. MARS incorporates cubic spline basis functions with recursive partitioning of the input space, uses statistical learning (least squares) instead of gradient descent, and predicts performance on test data during training using a cross-validation model to improve values of network parameters.

A manipulator control testbed - Implementation and applications
93A50594
FIALA, JOHN; WAVERING, ALBERT; LUMIA, RONALD (NIST, Gaithersburg, MD) In: Guidance and control 1992; Proceedings of the 15th Annual AAS Rocky Mountain Conference, Keystone, CO, Feb. 8-12, 1992 (A93-50576 21-18). San Diego, CA, Univelt, Inc., 1992, p. 319-334.

An implementation of the lower levels of the NASNIST Standard Reference Model (NASREM) Telerobot Control System Architecture has been developed at NIST. The implementation includes manipulator servo control, rate teleoperation, autonomous trajectory generation, and visual sensing. This paper describes how the system is designed to be a testbed for manipulator control via generic interfaces and a modular Ada software architecture. The multiprocessor hardware architecture which supports the software architecture for real-time operation is also described. The paper presents applications of the testbed system to specific manipulator control problems, including some example comparisons of different strategies for servo control and trajectory generation.

Telerobot control mode performance assessment
93A50593
ZIMMERMAN, WAYNE; BACKES, PAUL; CHIRIKJIAN, GREG (JPL, Pasadena, CA); (California Inst. of Technology, Pasadena) In: Guidance and control 1992; Proceedings of the 15th Annual AAS Rocky Mountain Conference, Keystone, CO, Feb. 8-12, 1992 (A93-50576 21-18). San Diego, CA, Univelt, Inc., 1992, p. 305-318.
With the maturation of various developing robot control schemes, it is becoming extremely important that the technical community evaluate the performance of these various control technologies against an established baseline to determine which technology provides the most reliable robust, and safe on-orbit robot control. The Supervisory Telerobotics Laboratory (STELER) at JPL has developed a unique robot control capability which has been evaluated by the NASA technical community and found useful for augmenting both the operator interface and control of intended robotic systems onboard the Space Station. As part of the technology development and prototyping effort, the STELER team has been evaluating the performance of different control modes; namely, teleoperation under position, or rate, control, teleoperation with force reflection and shared control. Nine trained subjects were employed in the performance evaluation involving several high fidelity servicing tasks. Four types of operator performance data were collected; task completion time, average force, peak force, and number of operator successes and errors. This paper summarizes the results of this performance evaluation.

Ground-remote control for space station telerobotics with time delay
93A50592
BACKES, PAUL G. (JPL, Pasadena, CA) In: Guidance and control 1992; Proceedings of the 15th Annual AAS Rocky Mountain Conference, Keystone, CO, Feb. 8-12, 1992 (A93-50576 21-18). San Diego, CA, Univelt, Inc., 1992, p. 285-303.
The study proposes a ground-remote telerobot control architecture which could be used for control of Space Station Freedom manipulators. The architecture provides two local-site operator control stations representing potential earth-based and remote Space Station-based operator control stations. A unified control system at the remote site provides autonomous, shared, and teleoperation control for single-and dual-arm task execution. An operational laboratory system which demonstrates the feasibility of various technologies in the proposed architecture, including teleoperation, shared control, and supervised autonomy, is described. Enhancements to the system currently under development, including remote site implementation in Ada, integration and control of a redundant 7-DOF manipulator, and local site advanced operator aids, are also described.

Interactive and cooperative sensing and control for advanced teleoperation
93A49443
LEE, SUKHAN; ZAPATA, EDUARDO; SCHENKER, PAUL S. (JPL, Pasadena; Southern California Univ., Los Angeles, CA); (Southern California Univ., Los Angeles, CA); (JPL, Pasadena, CA) In: Sensor fusion IV: Control paradigms and data structures; Proceedings of the Meeting, Boston, MA, Nov. 12-15, 1991 (A93-49438 21-63). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1992, p. 516-530.
This paper presents the paradigm of interactive and cooperative sensing and control as a fundamental mechanism of integrating and fusing the strengths of man and machine for advanced teleoperation. The interactive and cooperative sensing and control is considered as an extended and generalized form of traded and shared control. The emphasis of interactive and cooperative sensing and control is given to the distribution of mutually nonexclusive subtasks to man and machine, the interactive invocation of subtasks under the man/machine symbiotic relationship, and the fusion of information and decision-making between man and machine according to their confidence measures. The proposed interactive and cooperative sensing and control system is composed of such major functional blocks as the logical sensor system, the sensor-based local autonomy, the virtual environment formation, and the cooperative decision-making between man and machine. A case study is performed to demonstrate the feasibility of implementing the fundamental theory and system architecture of interactive and cooperative sensing and control, proposed for the new generation of teleoperation.

Continuous motion using task-directed stereo vision
93A49442
GAT, ERANN; LOCH, JOHN L. (JPL, Pasadena, CA) In: Sensor fusion IV: Control paradigms and data structures; Proceedings of the Meeting, Boston, MA, Nov. 12-15, 1991 (A93-49438 21-63). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1992, p. 294-298.
The performance of autonomous mobile robots performing complex navigation tasks can be dramatically improved by directing expensive sensing

and planning in service of the task. The task-direction algorithms can be quite simple. In this paper we describe a simple task-directed vision system which has been implemented on a real outdoor robot which navigates using stereo vision. While the performance of this particular robot was improved by task-directed vision, the performance of task-directed vision in general is influenced in complex ways by many factors. We briefly discuss some of these, and present some initial simulated results.

Operator performance with alternative manual control modes in teleoperation
93A49397
DAS, H.; ZAK, H.; KIM, W. S.; BEJCZY, A. K.; SCHENKER, P. S. (JPL, Pasadena, CA) Presence: Teleoperators and Virtual Environments (ISSN 1054-7460), vol. 1, no. 2, Spring 1992, p. 201-218.
Recent experiments conducted at the JPL comparing alternative manual control modes using the JPL Advanced Teleoperator system are described. Of particular interest were control modes that provide force reflection to the operator. The task selected for the experiment is a portion of the Solar Maximum Satellite Repair procedure we developed to demonstrate the repair of the Solar Maximum Satellite with teleoperators. The seven manual control modes evaluated in the experiment are combinations of manual position or resolved motion rate control with alternative control schemes for force reflection and remote manipulator compliance. Performance measures used were task completion times, average force and torque exerted during the execution of the task, and cumulative force and torque exerted. The results were statistically analyzed and they show that, in general, force reflection significantly improves operator performance and indicate that a specific force-reflecting scheme may yield the best performance among the control modes we tested. Also, our experiment showed that, for the selected task, the position control modes were preferable to the rate control modes and slave manipulator compliance reduced task interaction forces and torques.

Transforming human hand motion for telemanipulation
93A49394
SPEETER, THOMAS H. (AT&T Bell Labs., Holmdel, NJ) Presence: Teleoperators and Virtual Environments (ISSN 1054-7460), vol. 1, no. 1, Winter 1992, p. 63-79.
Manipulation by teleoperation (telemanipulation) offers an apparently straightforward and less computationally expensive route toward dextrous robotic manipulation than automated control of multifingered robotic hands. The functional transformation of human hand motions into equivalent robotic hand motions, however, presents both conceptual and analytical problems. This paper reviews and proposes algorithmic methods for transforming the actions of human hands into equivalent actions of slave multifingered robotic hands. Forward positional transformation is considered only, the design of master devices, feedforward dynamics, and force feedback are not considered although their importance for successful telemanipulation is understood. Linear, nonlinear, and functional mappings are discussed along with performance and computational considerations.

Teleprogramming - Toward delay-invariant remote manipulation
93A49392
FUNDA, JANEZ; LINDSAY, THOMAS S.; PAUL, RICHARD P. (Pennsylvania Univ., Philadelphia) Presence: Teleoperators and Virtual Environments (ISSN 1054-7460), vol. 1, no. 1, Winter 1992, p. 29-44.
The paper proposes a control methodology, called teleprogramming, which is a new approach to low-level task specification for a remotely located robotic system and which offers a practical intermediate solution to time-delayed remote manipulation. Teleprogramming combines the power of a graphic previewing display with the provision of real-time kinesthetic feedback, to allow the operator to interactively define the task to be performed remotely. The instructions are generated automatically, in real time, based on the operator's interaction with the simulated environment. The slave robot executes these commands delayed in time, making it possible for the operator to correct actions in case of an error. The paper describes the main components of the teleprogramming system and reports the preliminary results from the use of an experimental system.

Intelligent robotics; Proceedings of the International Symposium, Bangalore, India, Jan. 2-5, 1991
93A49350
VIDYASAGAR, M.; TRIVEDI, MOHAN M. (Centre for Artificial Intelligence and Robotics, Bangalore, India); (Tennessee Univ., Knoxville) New Delhi, Tata McGraw-Hill Publishing Co., Ltd. (SPIE Proceedings. Vol. 1571), 1991, 746 p. (For individual items see A93-49351 to A93-49360)
The present volume on intelligent robotics discusses parallel vision algorithms using sparse array representations, vision-based techniques for rotorcraft low-altitude flight, the design of direct-drive robots using indigenously developed dc torque motors, and an end-effector for 3D manipulation of multiple-ply apparel workpieces. Attention is given to a robot vision algorithm for manipulating objects in a cluttered scene, a sensor-based part feeding gate, the development of a four-axis robot for automation in the nuclear industry, and the design of a composite controller for a two-link flexible manipulator. Topics addressed include two-time scale control for an arm with joint and link compliance, point-to-point control of elastic joint robots, intelligent robotic polishing, and a robotic system for the inspection of turbine disks. Also discussed are measures of intensity of collision between convex objects and their efficient computation, efficient coordinated motion,

observer-based control laws for robotic manipulators, and multipolynomial resultant algorithms.

Controlled motion in an elastic world
93A46742
BOOK, WAYNE J. (Georgia Inst. of Technology, Atlanta) ASME, Transactions, Journal of Dynamic Systems, Measurement, and Control (ISSN 0022-0434), vol. 115, no. 2(B), June 1993, p. 252-261. (Previously announced in STAR as N93-18778)
The flexibility of the drives and structures of controlled motion systems are presented as an obstacle to be overcome in the design of high performance motion systems, particularly manipulator arms. The task and the measure of performance to be applied determine the technology appropriate to overcome this obstacle. Included in the technologies proposed are control algorithms (feedback and feed forward), passive damping enhancement, operational strategies, and structural design. Modeling of the distributed, nonlinear system is difficult, and alternative approaches are discussed. The author presents personal perspectives on the history, status, and future directions in this area.

Kinematics and control of a fully parallel force-reflecting hand controller for manipulator teleoperation
93A45598
BRYFOGLE, MARK D.; NGUYEN, CHARLES C.; ANTRAZI, SAMI S.; CHIOU, PETER C. (Science Applications International Corp., McLean, VA); (Catholic Univ. of America, Washington) Journal of Robotic Systems (ISSN 0741-2223), vol. 10, no. 5, July 1993, p. 745-766.
Design of a parallel force-reflecting hand controller that implements a friction- and inertia canceling control loop about the entire mechanism based on wrench sensing in the mechanism handgrip is discussed. Kinematics of the controller under consideration is analyzed and results are presented using a closed-form solution for the inverse kinematics and Newton-Raphson's method for the forward kinematics. Results indicate that the force control scheme based on a handgrip force sensor provides smaller steady-state errors than the scheme without a handigrip sensor.

Adaptive control of a Stewart platform-based manipulator
93A45596
NGUYEN, CHARLES C.; ANTRAZI, SAMI S.; ZHOU, ZHEN-LEI; CAMPBELL, CHARLES E., JR. (Catholic Univ. of America, Washington); (NASA, Goddard Space Flight Center, Greenbelt, MD) Journal of Robotic Systems (ISSN 0741-2223), vol. 10, no. 5, July 1993, p. 657-687.
A joint-space adaptive control scheme for controlling noncompliant motion of a Stewart platform-based manipulator (SPBM) was implemented in the Hardware Real-Time Emulator at Goddard Space Flight Center. The six-degrees of freedom SPBM uses two platforms and six linear actuators driven by dc motors. The adaptive control scheme is based on proportional-derivative controllers whose gains are adjusted by an adaptation law based on model reference adaptive control and Liapunov direct method. It is concluded that the adaptive control scheme provides superior tracking capability as compared to fixed-gain controllers.

Attitude control algorithm for free-flying space robot using thruster
93A45274
KOBAYASHI, NOBUYUKI; SAITO, OSAMU; YOSHIE, YUUKI; KURIHARA, HIROSHI Ishikawajima-Harima Engineering Review (ISSN 0578-7904), vol. 33, no. 1, Jan. 1993, p. 1-6.
An attitude control algorithm for a free-flying space robot to control thrusters is proposed. The motion of the manipulator on a space robot causes attitude deviation of the main body because of dynamic interaction. The proposed Disturbed-Torque Compensation Algorithm, a kind of feedforward control, considers the inertia force, calculated by the equation of motion, as the disturbance torque for the main body. The algorithm activates thrusters to compensate for the torque. The proposed algorithm is compared to the Time or Time-Energy Optimal Control algorithm. Simulation results for attitude deviations and input energy are discussed.

Linearization of manipulator dynamics using spatial operators
93A43725
JAIN, A.; RODRIGUEZ, G. (JPL, Pasadena, CA) IEEE Transactions on Systems, Man, and Cybernetics (ISSN 0018-9472), vol. 23, no. 1, Jan.-Feb. 1993, p. 239-248.
Linearized dynamics models for manipulators are useful in robot analysis, motion planning, and control applications. Techniques from the spatial operator algebra are used to obtain closed form operator expressions for two types of linearized dynamics models, the linearized inverse and forward dynamics models. Spatially recursive algorithms of O(n) and O(n-squared) complexity for the computation of the perturbation vector and coefficient matrices for the linearized inverse dynamics model are developed first. Subsequently, operator factorization and inversion identities are used to develop corresponding closed-form expressions for the linearized forward dynamics model (LFDM). Once again, these are used to develop algorithms of O(n) and O(n-squared) complexity for the computation of the perturbation vector and the coefficient matrices. The algorithms for the LFDM do not require the explicit computation of the mass matrix nor its numerical inversion and are also of lower complexity than the conventional O(n-cubed) algorithms.

Real-time collision avoidance in teleoperated whole-sensitive robot arm manipulators
93A43723
LUMELSKY, VLADIMIR J.; CHEUNG,

EDWARD (Wisconsin Univ., Madison); (NASA, Goddard Space Flight Center, Greenbelt, MD) IEEE Transactions on Systems, Man, and Cybernetics (ISSN 0018-9472), vol. 23, no. 1, Jan.-Feb. 1993, p. 194-203.
A hybrid robot teleoperation system is presented which makes use of the methodology of motion planning for whole-sensitive robots to assist the operator in generating collision-free motion in a master-slave robot arm manipulator system. The system combines operator commands with data from the sensitive skin to guarantee safe motion for the entire body of the robot arm. The arm avoids obstacles automatically and in real time and moves in a collision-free manner although no prior knowledge of the objects in the environment is available to the motion planning system and no constraints are imposed on the obstacle shapes. The operator is thus relieved of the task of providing safety of the robot arm and surrounding objects.

Visual specification of robot motion
93A42845
SHIU, Y. C.; CHONG, R.; RUNNER, K.; SCAGGS, T.; SETH, N.; CRAVEN, R. (Wright State Univ., Dayton, OH); (USAF, Aeronautical Systems Div., Wright-Patterson AFB, OH) In: NAECON 92; Proceedings of the IEEE 1992 National Aerospace and Electronics Conference, Dayton, OH, May 18-22, 1992. Vol. 2 (A93-42776 17-01). New York, Institute of Electrical and Electronics Engineers, Inc., 1992, p. 705-708. Research supported by NASA and Ohio Aerospace Inst.
The authors describe the use of stereo pairs of images to specify robot motion. The experimental setup includes a SUN workstation, a PUMA 560 robot, and an Imaging 151 vision system. An X-window environment displays stereo images of the work scene. Image processing is performed to extract linear edge segments from the images and the results are displayed on screen. Using a pointing device, the user selects a group of edges from the object relevant to the task. The 3D structure of this group of features is found by stereo triangulation and they can be displayed in 3D from any point of view. A viewpoint orthogonal to the plane defined by these 3D edges is used to specify the robot position relative to object position. The actual robot will then be moved to the specified position.

Principles of control for robotic excavation
93A42097
BERNOLD, LEONHARD E. (North Carolina State Univ., Raleigh) In: Engineering, construction, and operations in space III: Space '92; Proceedings of the 3rd International Conference, Denver, CO, May 31-June 4, 1992. Vol. 2 (A93-41976 17-12). New York, American Society of Civil Engineers, 1992, p. 1401-1412.
The issues of automatic planning and control systems for robotic excavation are addressed. Attention is given to an approach to understanding the principles of path and motion control which is based on scaled modeling and experimentation with different soil types and soil conditions. Control concepts for the independent control of a bucket are discussed, and ways in which force sensors could provide the necessary data are demonstrated. Results of experiments with lunar simulant showed that explosive loosening has a substantial impact on the energy needed during excavation. It is argued that through further laboratory and field research, 'pattern languages' for different excavators and soil conditions could be established and employed for robotic excavation.

Contact sensing from force measurements
93A41673
BICCHI, ANTONIO; SALISBURY, J. K.; BROCK, DAVID L. (MIT, Cambridge, MA) International Journal of Robotics Research (ISSN 0278-3649), vol. 12, no. 3, June 1993, p. 249-262. Research supported by Systems Development Foundation, Sandia National Labs., DARPA, CNR, and NATO.
This article addresses contact sensing (i.e., the problem of resolving the location of a contact, the force at the interface, and the moment about the contact normals). Called 'intrinsic' contact sensing for the use of internal force and torque measurements, this method allows for practical devices that provide simple, relevant contact information in practical robotic applications. Such sensors have been used in conjunction with robot hands to identify objects, determine surface friction, detect slip, augment grasp stability, measure object mass, probe surfaces, and control collision and for a variety of other useful tasks. This article describes the theoretical basis for their operation and provides a framework for future device design.

Fuzzy logic for adaptive control of complex robots and telerobots
93A40664
FRANKE, ERNEST A.; NEDUNGADI, ASHOK (Southwest Research Inst., San Antonio, TX) Society of Manufacturing Engineers, Maintaining and Supporting an Aircraft Fleet Conference, Dayton, OH, June 9-11, 1992. 8 p. Research supported by Southwest Research Inst.
A recently completed research program at Southwest Research Institute has developed a fuzzy logic controller for a redundant, four degree-of-freedom, planar manipulator. The manipulator end point trajectory can be specified by either a computer program (robot mode) or by manual input (teleoperator mode). The approach used expresses end-point error the location of manipulator joints and proximity to obstacles as fuzzy variables. Joint motions are determined by a fuzzy rule set without requiring solution of the inverse kinematic equations. Additional rules for sensor data and preferred manipulator configuration, eg. 'righty' or 'lefty', are easily accommodated. The procedure used to generate the fuzzy rules can be extended to higher DOF systems.

Robotic aircraft painting with SAFARI
93A40662
BERRY, HENRY K.; MATTHEWS, JOHN D. (Engineering, Inc., Hampton, VA) Society of Manufacturing Engineers, Maintaining and Supporting an Aircraft Fleet Conference, Dayton, OH, June 9-11, 1992. 11 p.
This paper discusses concept through installation and operating results of robotic aircraft painting at Robins AFB using a SAFARI to wash, prep, and paint F-15 aircraft with polyurethane and waterborne high-solid paints. The paper includes a discussion of how the same robotic system can be used for stripping aircraft.

Operator assistant systems - An experimental approach using a telerobotics application
93A39400
BOY, GUY A.; MATHE, NATHALIE (European Inst. of Cognitive Sciences and Engineering, Labage, France); (NASA, Ames Research Center, Moffett Field, CA) International Journal of Intelligent Systems (ISSN 0884-8173), vol. 8, 1993, p. 271-286.
This article presents a knowledge-based system methodology for developing operator assistant (OA) systems in dynamic and interactive environments. This is a problem both of training and design, which is the subject of this article. Design includes both design of the system to be controlled and design of procedures for operating this system. A specific knowledge representation is proposed for representing the corresponding system and operational knowledge. This representation is based on the situation recognition and analytical reasoning paradigm. It tries to make explicit common factors involved in both human and machine intelligence, including perception and reasoning. An OA system based on this representation has been developed for space telerobotics. Simulations have been carried out with astronauts and the resulting protocols have been analyzed. Results show the relevance of the approach and have been used for improving the knowledge representation and the OA architecture.

Adaptive robotic visual tracking - Theory and experiments
93A38206
PAPANIKOLOPOULOS, NIKOLAOS P.; KHOSLA, PRADEEP K. (Minnesota Univ., Minneapolis); (Carnegie Mellon Univ., Pittsburgh, PA) IEEE Transactions on Automatic Control (ISSN 0018-9286), vol. 38, no. 3, March 1993, p. 429-445.
This paper addresses the use of a vision sensor in the feedback loop within the Controlled Active Vision framework. Using this framework, algorithms are proposed for the solution of the robotic (eye-in-hand configuration) visual tracking and servoing problem. We state the problem of visual tracking as a problem of combining control with computer vision. We use the sum-of-squared differences (SSD) optical flow for the computation of the vector of discrete displacements. The measurements can be derived either from a single big window or from multiple small windows. These displacements are fed to an adaptive controller (self-tuning regulator) that creates commands for a robot control system. The whole algorithm is based on the on-line estimation of the relative distance of the target with respect to the camera. An important contribution of this work is that it requires only partial knowledge of the relative distance of the target with respect to the camera. This fact obviates the need for off-line calibration of the eye-in-hand robotic system. We have implemented, both in simulation and in experiments, three different adaptive control schemes, and the results are presented in this paper. The computational complexity and the experimental results demonstrate that the proposed algorithms can be implemented in real time.

A new neural net approach to robot 3D perception and visuo-motor coordination
93A37003
LEE, SUKHAN (JPL, Pasadena; Southern California Univ., Los Angeles, CA) In: IJCNN - International Joint Conference on Neural Networks, Baltimore, MD, June 7-11, 1992, Proceedings. Vol. 1 (A93-37001 14-63). New York, Institute of Electrical and Electronics Engineers, Inc., 1992, p. I-299 to I-307.
A novel neural network approach to robot hand-eye coordination is presented. The approach provides a true sense of visual error servoing, redundant arm configuration control for collision avoidance, and invariant visuo-motor learning under gazing control. A 3-D perception network is introduced to represent the robot internal 3-D metric space in which visual error servoing and arm configuration control are performed. The arm kinematic network performs the bidirectional association between 3-D space arm configurations and joint angles, and enforces the legitimate arm configurations. The arm kinematic net is structured by a radial-based competitive and cooperative network with hierarchical self-organizing learning. The main goal of the present work is to demonstrate that the neural net representation of the robot 3-D perception net serves as an important intermediate functional block connecting robot eyes and arms.

Application of principal base parameter analysis to design of adaptive robot controllers
93A35554
SHOWMAN, G. L.; LEAHY, M. B., JR. (USAF, Inst. of Technology, Wright-Patterson AFB, OH) In: 1992 IEEE International Conference on Robotics and Automation, 8th, Nice, France, May 12-14, 1992, Proceedings. Vol. 3 (A93-35501 13-63). Los Alamitos, CA, IEEE Computer Society Press, 1992, p. 1889-1894.
The feasibility of using principal base parameter analysis (PBPA) as an aid in the design and tuning of adaptive model-based controllers for industrial manipulators is investigated. Results from PBPA are utilized to select the minimal size of the adaptive

parameter vector and to develop a less heuristic procedure for controller tuning. The design procedure is illustrated by a simple two link example and then extended to the first three links of a PUMA-560. Experimental analysis contrasted with an adaptive model-based control (AMBC) design augmented with PBPA to a completely heuristic procedure used in previous research. The incorporation of PBPA into the AMBC design minimized the computational complexity while reducing the time and expertise necessary to tune the controller for satisfactory tracking efficacy.

Developments of new force reflecting control schemes and an application to a teleoperation training simulator
93A35545
KIM, WON S. (JPL, Pasadena, CA) In: 1992 IEEE International Conference on Robotics and Automation, 8th, Nice, France, May 12-14, 1992, Proceedings. Vol. 2 (A93-35501 13-63). Los Alamitos, CA, IEEE Computer Society Press, 1992, p. 1412-1419.
Two schemes of force reflecting control, position-error based force reflection and low-pass-filtered force reflection, both combined with shared compliance control, were developed for dissimilar master-slave arms. These schemes enabled high force reflection gains, which were not possible with a conventional scheme when the slave arm was much stiffer than the master arm. The experimental results with a peg-in-hole task indicated that the newly force reflecting control schemes combined with compliance control resulted in best task performances. As a related application, a simulated force reflection/shared compliance control teleoperation trainer was developed that provided the operator with the feel of kinesthetic force virtual reality.

Designing teleoperator architectures for transparency
93A35544
LAWRENCE, DALE A. (Colorado Univ., Boulder) In: 1992 IEEE International Conference on Robotics and Automation, 8th, Nice, France, May 12-14, 1992, Proceedings. Vol. 2 (A93-35501 13-63). Los Alamitos, CA, IEEE Computer Society Press, 1992, p. 1406-1411.
The author provides tools for analyzing the performance of various teleoperation systems, including the effects of communication delay. A general multivariable system architecture is utilized which includes all four types of data transmission between master and slave: force and position in both directions. It is shown that a proper use of all four channels is of critical importance in achieving high-performance telepresence in the sense of accurate transmission of task impedances to the operator. Achieved transparency and stability properties of two common architectures, as well as a transparency-optimized architecture are quantitatively compared on simplified one-degree-of-freedom examples.

Shared and traded telerobotic visual control
93A35529
PAPANIKOLOPOULOS, N. P.; KHOSLA, P. K. (Carnegie Mellon Univ., Pittsburgh, PA) In: 1992 IEEE International Conference on Robotics and Automation, 8th, Nice, France, May 12-14, 1992, Proceedings. Vol. 1 (A93-35501 13-63). Los Alamitos, CA, IEEE Computer Society Press, 1992, p. 878-885. Research supported by DARPA.
The authors address the problem of integrating the human operator with autonomous robotic visual tracking and servoing modules. A CCD (charge coupled device) camera is mounted on the end-effector of a robot and the task is to servo around a static or moving rigid target. In manual control mode, the human operator, with the help of a joystick and a monitor, commands robot motions in order to compensate for tracking errors. In shared control mode, the human operator and the autonomous visual tracking modules command motion along orthogonal sets of degrees of freedom. In autonomous control mode, the autonomous visual tracking modules are in full control of the servoing functions. Finally, in traded control mode, the control can be transferred from the autonomous visual modules to the human operator and vice versa. The authors present an experimental setup where all these different schemes have been tested. Experimental results of all modes of operation are presented and the related issues are discussed. In certain degrees of freedom the autonomous modules perform better than the human operator. On the other hand, the human operator can compensate fast for failures in tracking while the autonomous modules fail.

An advanced teleoperator control system - Design and evaluation
93A35526
LEE, SUKHAN; LEE, HAHK S. (JPL, Pasadena; Southern California Univ., Los Angeles, CA); (Southern California Univ., Los Angeles, CA) In: 1992 IEEE International Conference on Robotics and Automation, 8th, Nice, France, May 12-14, 1992, Proceedings. Vol. 1 (A93-35501 13-63). Los Alamitos, CA, IEEE Computer Society Press, 1992, p. 859-864.
The design goal of an advanced teleoperator control system is twofold: 1) to allow the operator's manual control to be robust to system nonlinearities such as time delays and operator's control errors, and 2) to support the high performance of teleoperation while reducing the operator's control burden by providing the master and slave arms with desirable dynamic properties and by allowing the slave arm to automatically perform such control tasks as compliance and force control in the form of task sharing. The authors present a novel teleoperator control system achieving the above design goal by taking the following into consideration: the human dynamics involved in generating control command based on visual and forced feedback is modeled and incorporated into the controller design and evaluation; the

dynamic characteristics of slave and master arms are actively modified in such a way as to implement the desirable dynamic characteristics; and the force feedback is redefined in terms of the combination of opposition and force discrepancies in order to establish the required man/machine dynamic coordination under shared control. The proposed control system with human dynamics in the control loop is simulated and compared with a number of conventional methods in the presence of human control errors and time delays.

A new control scheme for bilateral teleoperating systems - Lyapunov stability analysis
93A35524
STRASSBERG, Y.; GOLDENBERG, A. A.; MILLS, J. K. (Toronto Univ., Canada) In: 1992 IEEE International Conference on Robotics and Automation, 8th, Nice, France, May 12-14, 1992, Proceedings. Vol. 1 (A93-35501 13-63). Los Alamitos, CA, IEEE Computer Society Press, 1992, p. 837-842.
The authors investigate the Liapunov stability property of a control scheme for the bilateral master-slave teleoperator, first introduced by the authors in 1990. Given the nominal models of the master and slave dynamics, and using an approximate feedback linearization control, based on the earlier work of M. W. Spong and M. Vidyasagar (1987), it is shown that Liapunov stability can be obtained under the assumption that the deviation of the model from the true system satisfies certain norm inequalities. From these norm inequalities, it is shown that the tracking error (position/velocity and force/torque) is bounded and that sufficient conditions for Liapunov stability can be achieved. The control scheme is illustrated using the simulation of a 30-degree-of-freedom master-slave teleoperator, and the results are presented.

Real-time velocity feedback obstacle avoidance via complex variables and conformal mapping
93A35515
MEGHERBI, DALILA; WOLOVICH, W. A. (Brown Univ., Providence, RI) In: 1992 IEEE International Conference on Robotics and Automation, 8th, Nice, France, May 12-14, 1992, Proceedings. Vol. 1 (A93-35501 13-63). Los Alamitos, CA, IEEE Computer Society Press, 1992, p. 206-213.
A method for mobile robot motion planning is presented for both two- and three-dimensional robots. For the two-dimensional case, the algorithm is based on complex variable theory and conformal mapping. The method gives the robot the capability of avoiding obstacles more efficiently, smoothly, and at a constant curvilinear velocity. In order to establish the structure of the proposed velocity feedback obstacle avoidance scheme, several issues are addressed and successfully resolved. First, an analytical solution is derived for the case of circular obstacles. Second, the algorithm uses conformal mapping to establish the solution for an arbitrarily shaped obstacle based on the derived solution for a circular obstacle. The use of complex variable methodology with the objectives of exploiting the powerful technique of uniformal mapping constitutes the fundamental characteristic of the proposed technique. Third, by analogy, a solution to 3-D space-flying and subsea robots is also derived.

Selecting distinctive scene features for landmarks
93A35503
LI, SHIGANG; TSUJI, SABURO (Osaka Univ., Toyonaka, Japan) In: 1992 IEEE International Conference on Robotics and Automation, 8th, Nice, France, May 12-14, 1992, Proceedings. Vol. 1. Los Alamitos, CA, IEEE Computer Society Press, 1992,
Autonomous finding of landmarks for guiding long-distance navigation by a mobile is explored. In a trial navigation, the robot continuously views and memorizes scenes along the route. When the same route is subsequently pursued again, the robot locates and orients itself based on the memorized scene. Since the stream of images is highly redundant, it is transformed into an intermediate 2(1/2)-D representation, called the panoramic representation (PR), with a much smaller amount of data. Although the PR can be used for guidance of the autonomous navigation, it still contains a huge amount of data for a very long route. A human memorizes only very impressive objects along the route and uses them as landmarks. The robot also finds distinctive objects along the route and memorizes their features as well as spatial relationships for navigation guidance. Three-dimensional objects along the route are segmented in the PR by fusing range estimates and color attributes, and then a structure map representing their arrangement in space is obtained. In order to find distinctive objects used for the landmarks, the spatial relationships, shapes, and color attributes of the objects are examined.

Adaptive control of robotic manipulators using an extended Kalman filter
93A34404
GOURDEAU, R.; SCHWARTZ, H. M. (Ecole Polytechnique, Montreal, Canada); (Carleton Univ., Ottawa, Canada) ASME, Transactions, Journal of Dynamic Systems, Measurement, and Control (ISSN 0022-0434), vol. 115, no. 1, March 1993, p. 203-208.
This paper presents a new adaptive motion control scheme for robotic manipulators. This is an adaptive computed torque method (CTM) that requires only position measurements. These measurements and the input torques are used in an extended Kalman filter to estimate the inertial parameters of the full non-linear robot model as well as the joint positions and velocities. These estimates are used by the CTM to generate the input torques. The theory behind Kalman filtering provides clear guidelines on the selection of the design parameters for the controller when noise is present. Simulation results illustrate the performance of this scheme and demonstrate its noise rejection properties.

A trigonometric trajectory generator for robotic arms
93A33776
SIMON, DAN; ISIK, CAN (TRW, Inc., Ballistic Missiles Div., San Bernardino, CA); (Syracuse Univ., NY) International Journal of Control (ISSN 0020-7179), vol. 57, no. 3, March 1993, p. 505-517.
Interpolation of a robot joint trajectory is realized using trigonometric splines. This method is based on the assumption that joint-space knots have been generated from Cartesian knots by an inverse kinematics algorithm. The use of trigonometric splines results in smooth joint trajectories and is amenable to real-time obstacle avoidance. Some of the spline parameters can be chosen to minimize an objective function (e.g. jerk or energy). If the objective function is minimum jerk, a closed-form solution is obtained. This paper introduces a trajectory interpolation algorithm, discusses a method for trajectory optimization, and includes simulation examples.

System architecture for asynchronous multi-processor robotic control system
93A31033
STEELE, ROBERT D.; LONG, MARK; BACKES, PAUL (JPL, Pasadena, CA) AIAA, AHS, and ASEE, Aerospace Design Conference, Irvine, CA, Feb. 16-19, 1993. 8 p.
The architecture for the Modular Telerobot Task Execution System (MOTES) as implemented in the Supervisory Telerobotics (STELER) Laboratory is described. MOTES is the software component of the remote site of a local-remote telerobotic system which is being developed for NASA for space applications, in particular Space Station Freedom applications. The system is being developed to provide control and supervised autonomous control to support both space based operation and ground-remote control with time delay. The local-remote architecture places task planning responsibilities at the local site and task execution responsibilities at the remote site. This separation allows the remote site to be designed to optimize task execution capability within a limited computational environment such as is expected in flight systems. The local site task planning system could be placed on the ground where few computational limitations are expected. MOTES is written in the Ada programming language for a multiprocessor environment.

Telerobotic tasks requirements for planetary missions
93A29146
THOMAS, MARIE-CLAUDE; OCCELLO, MICHEL; TIGLI, JEAN-YVES (Nice Univ., Valbonne, France) In: Cooperative intelligent robotics in space III; Proceedings of the Meeting, Boston, MA, Nov. 16-18, 1992 (A93-29101 10-54). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1992, p. 505-513.
Some aspects of software design for telerobotic tasks are examined, with emphasis on spatial domain with its particular requirements. A blackboard approach to building specific architectures (both on-board and remote) is proposed. The design and development of a hybrid distributed blackboards system based on a parallel blackboard model are discussed. Two models are presented (for static decomposition of mission and dynamic decision-making) which satisfy the same requirements of software engineering, such as genericity. They adopt a functional approach and emphasize the autonomy as a dynamic decision-making criterion. A software control architecture for space telerobotics and different control mechanism filters are illustrated.

Manipulator control for rover planetary exploration
93A29145
CAMERON, JONATHAN M.; TUNSTEL, EDWARD; NGUYEN, TAM; COOPER, BRIAN K. (JPL, Pasadena, CA) In: Cooperative intelligent robotics in space III; Proceedings of the Meeting, Boston, MA, Nov. 16-18, 1992 (A93-29101 10-54). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1992, p. 495-504.
An anticipated goal of Mars surface exploration missions will be to survey and sample surface rock formations which appear scientifically interesting. In such a mission, a planetary rover would navigate close to a selected sampling site and the remote operator would use a manipulator mounted on the rover to perform a sampling operation. Techniques for accomplishing the necessary manipulation for the sampling components of such a mission have been developed and are presented. We discuss the implementation of a system for controlling a seven (7) degree of freedom Puma manipulator, equipped with a special rock gripper mounted on a planetary rover prototype, intended for the purpose of performing the sampling operation. Control is achieved by remote teleoperation. This paper discusses the real-time force control and supervisory control aspects of the rover manipulation system. Integration of the Puma manipulator with the existing distributed computer architecture is also discussed. The work described is a contribution toward achieving the coordinated manipulation and mobility necessary for a Mars sample acquisition and return scenario.

Robot free-flyers in space extravehicular activity
93A29141
WEIGL, HARALD; ALEXANDER, HAROLD L. (MIT, Cambridge, MA) In: Cooperative intelligent robotics in space III; Proceedings of the Meeting, Boston, MA, Nov. 16-18, 1992 (A93-29101 10-54). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1992, p. 458-469.
Attention is given to the development of a remote robot with maneuverability and dexterity comparable to that of a space-suited astronaut with a manned maneuvering unit capable of handling many of the tasks currently planned for astronauts during EVA. A real-time vision-based navigation and control system for an underwater space robot simulator, the Submersible for Telerobotic and Astronautical

Research (STAR) is examined. The system, implemented with standard, inexpensive computer hardware, exhibits excellent performance and robustness characteristics for a variety of applications, including automatic station-keeping and large controlled maneuvers. Experimental results are presented which indicate the precision, accuracy, and robustness to disturbances of the vision-based control system. The study proves the feasibility of using vision-based control and navigation for remote robots and provides a foundation for developing a system for general space robot tasks.

Intelligent virtual interfaces for telerobotics
93A29136
GRINSTEIN, GEORGES G.; MAYBURY, MARK T.; MITCHELL, RICHARD B. (Mitre Corp., Bedford, MA) In: Cooperative intelligent robotics in space III; Proceedings of the Meeting, Boston, MA, Nov. 16-18, 1992 (A93-29101 10-54). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1992, p. 401-408.
Research in two key areas of intelligent interfaces to support teleoperation - intelligent virtual interfaces and plan-based communication - is described. The former promises a visual, auditory, and tactile experience, and the latter promises more natural and effective communications. Ways in which these capabilities might fit into a virtual reality interface for teleoperation are shown. A device integrator couples physical (e.g., dataglobe and eye-tracker) and linguistic input, which is then interpreted by a plan recognizer which would interpret both the communicative action as well as physical action intended by the operator. Once an action was performed by the remote physical or simulated (for training) robot, the results would be communicated to the user via a variety of modes, including visual, auditory, and tactile. These components need to be integrated and then evaluated.

Teleprogramming a cooperative space robotic workcell for Space Station
93A29109
HAULE, D. D.; NOORHOSSEINI, S. M.; MALOWANY, A. S. (McGill Univ., Montreal, Canada) In: Cooperative intelligent robotics in space III; Proceedings of the Meeting, Boston, MA, Nov. 16-18, 1992 (A93-29101 10-54). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1992, p. 102-116.
Robotics and automation in remote hostile enviroments such as space (planet) exploration, for which working conditions - environment model and robot operating conditions - are unknown or very partially known, are studied. Several interrelated topics for Space Station automation using a teleprogrammable space robotic workcell (SRW) are discussed. The operation rationale for SRW is to free up crew time with the ultimate goal of making on-board crew involvement in SRW tasks optional, while solving the problem of 'automation of operator or supervisory control'. The key issues of task level teleprogramming as an attribute for operating and decisional autonomy vs the concepts of classical teleoperation and telerobotics are also addressed.

Flight Telerobotic Servicer legacy
93A29106
SHATTUCK, PAUL L.; LOWRIE, JAMES W. (Martin Marietta Astronautics Group, Denver, CO) In: Cooperative intelligent robotics in space III; Proceedings of the Meeting, Boston, MA, Nov. 16-18, 1992 (A93-29101 10-54). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1992, p. 60-74.
The technology evolution that stemmed from developing and integrating a dexterous robot into a manned system, the Space Shuttle, is traced. Emphasis is placed on the safety and reliability requirements for a man-rated system as the critical factors which drive the overall system architecture. Task requirements and operational concepts for servicing and maintenance of space platforms, origins of technology for dexterous robotic systems, issues associated with space qualification of components, and development of the industrial base to support space robotics are also discussed. The Flight Telerobotic Servicer (FTS), developed to enhance and provide a safe alternative to the human presence in space, had completed the major component development activities for the flight system at the point of termination. The FTS Technology Capture Program provides a mechanism for transfering the component technologies to the user community and could serve as a focal point for the A&R program thrust in on-orbit servicing.

Real time proximity cues for teleoperation using model based force reflection
93A27033
BRUNO, GUY; MORGENTHALER, MATTHEW K. (Martin Marietta Civil Space and Communications Co., Denver, CO) In: Cooperative intelligent robotics in space II; Proceedings of the Meeting, Boston, MA, Nov. 12-14, 1991 (A93-27001 09-54). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1992, p. 346-355.
The problem of providing model based proximity cues using force reflection for teleoperation under time delay is addressed. A novel use of artificial potential fields is proposed as a teleoperator aid to efficiently provide a predictive tactile display. Several new artificial potential models are presented which are used to convey accurate shape and proximity information by generating handcontroller forces based on the potential gradient. These new potential gradients are shown to have an efficient implementation via exact computation as a neural network. A real time prototype implementation and integration with Martin Marietta's teleautonomous testbed, is discussed. Evaluations are made with human operators performing tasks using industrial manipulators under time delay scenarios.

Interactive Scene Analysis Module - A sensor-database fusion system for telerobotic environments
93A27032
COOPER, ERIC G.; VAZQUEZ, SIXTO L.; GOODE, PLESENT W. (NASA, Langley Research Center, Hampton, VA) In: Cooperative intelligent robotics in space II; Proceedings of the Meeting, Boston, MA, Nov. 12-14, 1991 (A93-27001 09-54). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1992, p. 334-345.
Accomplishing a task with telerobotics typically involves a combination of operator control/ supervision and a 'script' of preprogrammed commands. These commands usually assume that the location of various objects in the task space conform to some internal representation (database) of that task space. The ability to quickly and accurately verify the task environment against the internal database would improve the robustness of these preprogrammed commands. In addition, the on-line initialization and maintenance of a task space database is difficult for operators using Cartesian coordinates alone. This paper describes the Interactive Scene' Analysis Module (ISAM) developed to provide taskspace database initialization and verification utilizing 3-D graphic overlay modelling, video imaging, and laser radar based range imaging. Through the fusion of taskspace database information and image sensor data, a verifiable taskspace model is generated providing location and orientation data for objects in a task space. This paper also describes applications of the ISAM in the Intelligent Systems Research Laboratory (ISRL) at NASA Langley Research Center, and discusses its performance relative to representation accuracy and operator interface efficiency.

Incorporating robot vision in tele-autonomous systems
93A27031
LEJUN, SHAO; VOLZ, RICHARD; CONWAY, LYNN; WALKER, M. W. (Nanyang Technological Univ., Singapore); (Texas A & M Univ., College Station); (Michigan Univ., Ann Arbor) In: Cooperative intelligent robotics in space II; Proceedings of the Meeting, Boston, MA, Nov. 12-14, 1991 (A93-27001 09-54). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1992, p. 323-333.
A new method is proposed to tele-control the movement of a remote robot when the movement involves contact with objects and when the control involves a significant time delay. In this method, a vision system is incorporated into the tele-autonomous systems. The vision system is used to do vision sensory information feedback to update local world model and to implement a relative move mode to control the remote robot. This method will effectively overcome some of the limitations of current tele-robot control systems.

A telerobotic virtual control system
93A27030
ZHAI, SHUMIN; MILGRAM, PAUL (Toronto Univ., Canada) In: Cooperative intelligent robotics in space II; Proceedings of the Meeting, Boston, MA, Nov. 12-14, 1991 (A93-27001 09-54). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1992, p. 311-322. Research supported by Defence and Civil Inst. of Environmental Medicine.
A project to develop a telerobotic virtual control capability, currently underway at the University of Toronto, is described. The project centers on a new mode of interactive telerobotic control based on the technology of combining computer generated stereographic images with remotely transmitted stereoscopic video images. A virtual measurement technique, in conjunction with a basic level of digital image processing, comprising zooming, parallax adjustment, edge enhancement, and edge detection, have been developed to assist the human operator in visualization of the remote environment and in spatial reasoning. The aim is to maintain target recognition, tactical planning and high level control functions in the hands of the human operator, with the computer performing low level computation and control. Control commands initiated by the operator are implemented through manipulation of a virtual image of the robot system, merged with a live video image of the remote scene. This paper discusses the philosophy and objectives of the project, with emphasis on the underlying human factors considerations in the design, and reports the progress made to date in this effort.

World model and its uncertainty in supervisory robot control
93A27027
PARK, JONG H.; SHERIDAN, THOMAS B. (MIT, Cambridge, MA) In: Cooperative intelligent robotics in space II; Proceedings of the Meeting, Boston, MA, Nov. 12-14, 1991 (A93-27001 09-54). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1992, p. 278-288.
This paper describes new methods to deal with uncertainty in the position and orientation of objects in the world model in the context of robot teleoperations. The virtual obstacle (object) is defined to represent objects with uncertainty bounds, which are constructed by the operator, who uses geometric data base and a 6 d.o.f. input device, while viewing video displays. These virtual obstacles are updated as the cameras move. Also a new method to build the world model by so called 'flying-and-matching' is introduced. Experiments have been performed with human subjects to evaluate the proposed schemes.

Using qualitative reasoning for robot task planning
93A27015
SCHAEFER, PHIL (Martin Marietta Advanced Computing Technology, Denver, CO) In: Cooperative intelligent robotics in space II; Proceedings of

the Meeting, Boston, MA, Nov. 12-14, 1991 (A93-27001 09-54). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1992, p. 139-148.
Application of qualitative reasoning (QR) techniques to describe reasoning tasks for different classes of complex systems is discussed. It is shown that effective task planning for robotic systems can be performed using a qualitative, model-based paradigm. This approach has certain advantages over the usual operator-based techniques. The robotics workspace can be modeled modularly. Nonlinear methods and the truth maintenance system make the planning efficient, which allows complex search spaces to be searched with reasonable response time. QR representation for robot task planning using the Multi Purpose Causal (MPC) software tool can be used for exception detection, contingency identification, and contingency recovery. It is concluded that the major advantage of the QR approach is that all of the knowledge to perform each of the planning and failure management tasks is contained in one model.

Time-optimal trajectory generation for coordinated robotic manipulators using cell-to-cell mapping method
93A27013
WANG, FEI-YUE; PU, BING (Arizona Univ., Tucson) In: Cooperative intelligent robotics in space II; Proceedings of the Meeting, Boston, MA, Nov. 12-14, 1991 (A93-27001 09-54). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1992, p. 115-122.
A cell-to-cell mapping method is used to solve the problem of optimal trajectory generation for coordinated robotic manipulators handling a common object along specified geometric paths. The method is based on the cell state concept in conjunction with discretized controls and cost functions. A hierarchical search algorithm which makes it possible to implement parallel computation and to reduce the computation time is proposed.

Planning and executing visually constrained robot motions
93A27011
FOX, ARMANDO; CASTANO, ANDRES; HUTCHINSON, SETH (Illinois Univ., Urbana) In: Cooperative intelligent robotics in space II; Proceedings of the Meeting, Boston, MA, Nov. 12-14, 1991 (A93-27001 09-54). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1992, p. 90-97.
Despite progress in visual servo control of robot motions, to date the corresponding motion planning problem has not been investigated. In this paper, we present an implemented planner for the special case of a polyhedral world, extending previous preimage type planners to exploit visual constraint surfaces in a fixed-camera robotic system featuring closed-loop visual servo control. We present the mathematics of a hybrid (visual/position feedback) resolved-rate motion control strategy for executing these plans, featuring projection equations defined solely in terms of a small set of observable parameters that are directly obtained from our calibration process. We conclude with experimental results, a description of ongoing research and the contribution of our work to date.

Controller design for a force-reflecting teleoperator system with kinematically dissimilar master and slave
93A23844
JANSEN, J. F.; KRESS, R. L.; BABCOCK, S. M. (Oak Ridge National Lab., TN) ASME, Transactions, Journal of Dynamic Systems, Measurement, and Control (ISSN 0022-0434), vol. 114, no. 4, Dec. 1992, p. 641-649. Research sponsored by USAF.
The purpose of this paper is to develop a controller for a force-reflecting teleoperator system having kinematically dissimilar master and slave. The controller is a stiffness controller for both the master and slave. A mathematical problem associated with representing orientations using Euler angles is described, and Euler parameters are proposed as a solution. The basic properties of Euler parameters are presented, specifically those pertaining to stiffness control. The stiffness controller for both the master and the slave is formulated using Euler parameters to represent orientation and a Liapunov stability proof is presented for the controller. The master portion of the control scheme is implemented on a six-degree-of-freedom master.

Space based robot manipulators - Dynamics of contact and trajectory planning for impact minimization
93A22827
WEE, LIANG-BOON; WALKER, MICHAEL W. (Michigan Univ., Ann Arbor) In: 1992 American Control Conference, 11th, Chicago, IL, June 24-26, 1992, Proceedings. Vol. 1 (A93-22776 07-63). Piscataway, NJ, Institute of Electrical and Electronics Engineers, 1992, p. 771-775.
The authors consider contact between free-flying space robots, and the minimization of the impulse at impact. They begin with a presentation of a model of space robot which takes into account external applied forces. A contact model which considers both linear and angular motion between contacting systems is presented. Two approaches for trajectory planning in Cartesian space are discussed, and a strategy for achieving both the primary objective of trajectory tracking in Cartesian space and the secondary objective of impact minimization through configuration space planning is presented. The strategy was tested on a 15 degree-of-freedom space robot, and simulation results are presented.

Research state of the art of mobile robots in China
93A19109
WU, LIN; ZHAO, JINGLUN; ZHANG, PENG; LI, SHIQING (Harbin Inst. of Technology, China);

(Shenyang Inst. of Automation, China); (Changsha Inst. of Technology, China); (Shenyang Inst. of Automation, China) In: Mobile robots V; Proceedings of the Meeting, Boston, MA, Nov. 8, 9, 1990 (A93-19070 05-63). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1991, p. 598-601.
Mobile robots developed in China for applications in dangerous environments are briefly described. They include a master-slave telerobot, a six-legged robot, a remote inspection robot for wall surface travelling, a versatile crawler moving robot, and an autonomous mobile robot.

Plan-behavior interaction in autonomous navigation
93A19100
LIM, WILLIE; EILBERT, JIM (Grumman Corporate Research Center, Bethpage, NY) In: Mobile robots V; Proceedings of the Meeting, Boston, MA, Nov. 8, 9, 1990 (A93-19070 05-63). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1991, p. 464-475.
A scheme for plan-behavior interaction in a reactive robot for navigating in an indoor environment is presented which is based on relating behaviors to higher level plans. This approach makes possible the interaction between reactive behaviors and more explicit and deliberate reasoning processes. The capability of subsumption based robots has been extended by allowing higher level reasoning processes to tune the selection and activation of behaviors. The robot's overall behavior can be specialized and optimized to the specific goal or mission. Particular attention is given to the multiagent architecture for script-based navigation being developed for a robot called SmartyCat.

Environment model for mobile robots indoor navigation
93A19099
ROTH-TABAK, YUVAL; WEYMOUTH, TERRY E. (Michigan Univ., Ann Arbor) In: Mobile robots V; Proceedings of the Meeting, Boston, MA, Nov. 8, 9, 1990 (A93-19070 05-63). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1991, p. 453-463.
An autonomous mobile robot must be able to combine uncertain sensory information with prior knowledge of the world. Moreover, these operations have to be performed fast enough to be able to react to the changes in the world. This paper presents a model-driven system for a real-time indoor mobile robot. As the robot is constantly in motion, information from an Environment Model is used to anticipate information-rich features and to direct selective sensing. Uncertain sensor information is combined with prior World Model knowledge to reduce uncertainty, and the remaining uncertainty is directly represented by flexible ranges of values. We present a hall-following robot, based on this system, which exhibits real-time navigation performance. It does this despite primitive and relatively slow sensing, motor control, and communications capabilities.
This system combines sensing, action, and cognition, which are the major building blocks for any autonomous system.

Coping with complexity in the navigation of an autonomous mobile robot
93A19098
DODDS, DAVID R. In: Mobile robots V; Proceedings of the Meeting, Boston, MA, Nov. 8, 9, 1990 (A93-19070 05-63). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1991, p. 448-452.
This paper discusses the integrated use of dynamic systems theory, neural networks and evolutionary programming methods as a means of coping with complexity in automatic plan generation. Plan elements representing actions are mapped into phase-space and are examined for stability by searching for and identifying any 'attractors'. A knowledge-based system for doing this is described. As a means of coping with unexpected environments modifications of plans are made by the planning system using an evolutionary programming method coupled with a neural network approach.

Towards a versatile control system for mobile robots
93A19092
NOREILS, FABRICE R. (Carnegie Mellon Univ., Pittsburgh, PA) In: Mobile robots V; Proceedings of the Meeting, Boston, MA, Nov. 8, 9, 1990 (A93-19070 05-63). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1991, p. 384-396.
The goal of a mobile robot is not only to perform a large variety of tasks but also to adapt its behavior to the dynamic of the environment. Such a robot needs both reflexive and planning capabilities. Moreover, we wish that a mobile robot be able to coordinate its activity with other mobile robots. This paper is intended to show that the integration of all these capabilities (reflexivity, planning, and coordination) is feasible; in order to achieve this goal, a new robot architecture is proposed. This architecture is composed of three levels: functional, control, and planner. Furthermore, this architecture provides important features such as a progressive and programmable reactivity, robustness, additivity, and versatility. This paper emphasizes the control level and how it is used by the planner level. In order to demonstrate the feasibility of such an approach, a complete implementation of this architecture on our mobile robot, including experiments, are described.

Intelligent piloting tools for control of an autonomous mobile robot
93A19091
MALOTAUX, E.; ALIMENTI, R.; BOGAERT, M.; GASPART, P. (Centre de Recherches Scientifiques et Techniques de l'Industrie des Fabrications Mecaniques, Brussels, Belgium) In: Mobile robots V; Proceedings of the Meeting, Boston, MA, Nov. 8, 9, 1990 (A93-19070 05-63). Bellingham, WA,

Society of Photo-Optical Instrumentation Engineers, 1991, p. 372-383. Research supported by IRSIA, ACEC, Elbicon, et al.
Piloting procedures based on a pilot control algorithm (Autopil) are described including an off-line graph-search path planner (Pilastar) and on-line constrained piloting (Pilcpp). This very precise, flexible and inexpensive in computation time path execution control algorithm produces natural trajectories and takes into account all the physical constraints on speed and acceleration.

Hybrid navigational control scheme for autonomous platforms
93A19086
HOLLAND, JOHN; EVERETT, H. R.; GILBREATH, G. A. (Cybermotion, Inc., Roanoke, VA); (U.S. Navy, Naval Ocean Systems Center, San Diego, CA) In: Mobile robots V; Proceedings of the Meeting, Boston, MA, Nov. 8, 9, 1990 (A93-19070 05-63). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1991, p. 291-298.
A hybrid navigational scheme capable of periodically resetting the heading and position of the robot using a priori knowledge of navigational cues in the environment is presented. The scheme integrates the desired features of guidepath following, unrestricted path planning, and virtual path navigation into a robust navigational package better able to cope with the varied demands of real-world operation. The path planner uses fixed guidepaths and preprogrammed paths whenever possible, but maintains the ability to roam freely about the workspace.

Impact of uncertain terrain models on the weighted region problem
93A19084
MOBASSERI, BIJAN G. (Villanova Univ., PA) In: Mobile robots V; Proceedings of the Meeting, Boston, MA, Nov. 8, 9, 1990 (A93-19070 05-63). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1991, p. 270-277.
Outdoor navigation is characterized by motions through regions of varied terrain. The weighted region problem (WRP), is a generalization of the obstacle avoidance problem with 1/infinity cost structure. By assigning indices to surface patches proportional to their traversability, WRP seeks a path with the shortest length, in the weighted sense. This work generalizes the WRP paradigm by stating that the traversability indices may only be available through a probability distribution. The reported indices, therefore, are not an exact description of the terrain, rather, they are an observation drawn from their respective distributions. Development of a decision basis directing the search is an objective of this paper.

Safe motion planning for mobile agents - A model of reactive planning for multiple mobile agents
93A19083
FUJIMURA, KIKUO (Oak Ridge National Lab., TN) In: Mobile robots V; Proceedings of the Meeting, Boston, MA, Nov. 8, 9, 1990 (A93-19070 05-63). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1991, p. 260-269.
The problem of motion planning for multiple mobile agents is studied. Each planning agent independently plans its own action based on its map which contains a limited information about the environment. In an environment where more than one mobile agent interacts, the motions of the robots are uncertain and dynamic. A model for reactive agents is described and simulation results are presented to show their behavior patterns.

Terrain classification in navigation of an autonomous mobile robot
93A19076
DODDS, DAVID R. In: Mobile robots V; Proceedings of the Meeting, Boston, MA, Nov. 8, 9, 1990 (A93-19070 05-63). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1991, p. 82-89.
In this paper we describe a method of path planning that integrates terrain classification (by means of fractals), the certainty grid method of spatial representation, Kehtarnavaz Griswold collision-zones, Dubois Prade fuzzy temporal and spatial knowledge, and non-point sized qualitative navigational planning. An initially planned ('end-to-end') path is piece-wise modified to accommodate known and inferred moving obstacles, and includes attention to time-varying multiple subgoals which may influence a section of path at a time after the robot has begun traversing that planned path.

Real-time map-building for fast mobile robot obstacle avoidance
93A19075
BORENSTEIN, JOHANN; KOREN, YORAM (Michigan Univ., Ann Arbor) In: Mobile robots V; Proceedings of the Meeting, Boston, MA, Nov. 8, 9, 1990 (A93-19070 05-63). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1991, p. 74-81.
This paper introduces HIMM (histogramic in-motion mapping), a new method for real-time map building with a mobile robot in motion. HIMM represents data in a two-dimensional array (called a histogram grid) that is updated through rapid continuous sampling of the onboard range sensors during motion. Rapid in-motion sampling results in a statistical map representation that is well-suited to modeling inaccurate and noisy range-sensor data. HIMM is integral part of an obstacle avoidance algorithm and allows the robot to immediately use the mapped information in real-time obstacle-avoidance. The benefits of this integrated approach are twofold: (1) quick, accurate mapping; and (2) safe navigation of the robot toward a given target. HIMM has been implemented and tested on a mobile robot. Its dual functionality was demonstrated through numerous tests in which maps of unknown obstacle courses were created, while the robot

simultaneousy performed real-time obstacle avoidance maneuvers at speeds of up to 0.78 m/sec.

Vehicle path planning via dual world representations
93A19072
PECK, ALEX; BREUL, HARRY (Grumman Corporate Research Center, Bethpage, NY) In: Mobile robots V; Proceedings of the Meeting, Boston, MA, Nov. 8, 9, 1990 (A93-19070 05-63). Bellingham, WA, Society of Photo-Optical Instrumentation Engineers, 1991, p. 30-38.
A technique is developed whereby a mobile robot equipped with sonar sensors autonomously explores a hallway environment, and during exploration dynamically builds two types of maps: a graph of places defined by distinctive sonar events, and a grid map from dead reckoning data that is accurate in the neighborhood of a place. With both maps available, the robot can quickly plan a path between arbitrary locations, and then define a sequence of behaviors that will move the robot along the selected path. Robust performance is achieved by dividing the computational processes into two parallel operations. Time-critical, low-level behaviors like driving and steering in the exploratory mode are controlled by an onboard computer that uses sonar data as input to simple subsumption-based algorithms. Higher level, more computationally intense, and less-time-critical activities like place designation, map making, display generation, and path planning are performed in parallel on a remote computer that fetches sonar data and issues high-level commands via a radio link.

Teleoperation to robotics at Langley Research Center
93A18569
PENNINGTON, JACK E. (NASA, Langley Research Center, Hampton, VA) Journal of Applied Intelligence, vol. 2, 1992, p. 155-162.
Experience of NASA Langley Research Center in teleoperation, telerobotics, and robotics in applications related to possible space tasks is reviewed. Shared control based on manual and sensor blending in a rate command control system made it possible to simultaneously control two or more manipulators executing a telerobotic task from a single hand controller. It is concluded that telerobotics combines the best features of teleoperation and robotics and is sufficiently mature for simple space tasks. Robotics is considered to be feasible but less mature and must be highly reliable.

Telerobotics, automation, and human supervisory control
93A17571
SHERIDAN, THOMAS B. (MIT, Cambridge, MA) Cambridge, MA, MIT Press, 1992, 414 p.
A survey is presented of teleoperation, telerobotics, and supervisory control. This is a new form of technology that allows humans to work through machines in hazardous environments and control complex systems such as aircraft and nuclear power plants. The general topics addressed are: theory and models of supervisory control; supervisory control of anthropomorphic teleoperators for space, undersea, and other applications; supervisory control in transportation, process, and other automated systems; and social implications of telerobotics, automation, and supervisory control.

Optimal motion planning of a multiple-robot system based on decomposition coordination
93A17384
CELA, ARBEN S.; HAMAM, YSKAUNDAR (Ecole Superieure d'Ingenieurs en Electrotechnique et Electronique, Noisy-le-Grand, France) IEEE Transactions on Robotics and Automation (ISSN 1042-296X), vol. 8, no. 5, Oct. 1992, p. 585-596.
A solution to the problem of optimal trajectory planning of a multiple-robot system in the presence of obstacles is presented which is based on nonlinear programming and decomposition coordination. A decomposition method is used to reduce the problem to the single-robot level, and the augmented Lagrangian method is used to treat the problem of a single robot in the presence of obstacles. When applied to large-scale optimization problems, the methodology allows the possibility of a modular approach to the solution. The approach, which is also applicable to the single-robot case, reduces the computational effort and allows the use of the best optimization algorithm for a given optimization problem.

Position estimation for an autonomous mobile robot in an outdoor environment
93A17383
TALLURI, RAJ; AGGARWAL, J. K. (Texas Univ., Austin) IEEE Transactions on Robotics and Automation (ISSN 1042-296X), vol. 8, no. 5, Oct. 1992, p. 573-584.
This paper presents a solution to the position estimation problem of an autonomous land vehicle navigating in an unstructured mountainous terrain. A digital elevation map (DEM) of the area in which the robot is to navigate is assumed to be given. It is also assumed that the robot is equipped with a camera that can be panned and tilted, a compass, and an altimeter. No recognizable landmarks are assumed to be present in the environment in which the robot is to navigate, and the robot is not assumed to have an inital estimate of its position. The solution presented here makes use of the DEM information, and structures the problem as a constrained search paradigm by searching the DEM for the possible robot location. The algorithm is made robust to errors in the imaging process by accounting for worst case errors. The approach is tested using real terrain data of areas in Colorado and Texas. The method is suitable for use in outdoor mobile robots and planetary rovers.

Exact robot navigation using artificial potential functions
93A17380
RIMON, ELON; KODITSCHEK, DANIEL E. (Stanford Univ., CA); (Yale Univ., New Haven, CT) IEEE Transactions on Robotics and Automation (ISSN 1042-296X), vol. 8, no. 5, Oct. 1992, p. 501-518.
A new methodology for exact robot motion planning and control is presented which combines the purely kinematic path planning problem with the lower feedback controller design. It is shown, in particular, how navigation functions can be constructed from a geometric description of the free configuration space. The computational complexity of the resulting algorithm is assessed, and results of a series of simulation studies are presented. Finally suggestions are made concerning the extension of ideas presented here.

Adaptive multisensor fusion for planetary exploration rovers
93A13664
COLLIN, MARIE-FRANCE; KUMAR, KRISHEN; PAMPAGNIN, LUC-HENRI (NASA, Johnson Space Center, Houston, TX); (ITMI, Meylan, France) In: Artificial intelligence, robotics, and automatic control, applied to space /Intelligence artificielle, robotique et automatique, appliquees a l'espace/. Toulouse, Cepadues-Editions, 1992, p. 113-116. Research supported by NATO.
The purpose of the adaptive multisensor fusion system currently being designed at NASJohnson Space Center is to provide a robotic rover with assured vision and safe navigation capabilities during robotic missions on planetary surfaces. Our approach consists of using multispectral sensing devices ranging from visible to microwave wavelengths to fulfill the needs of perception for space robotics. Based on the illumination conditions and the sensors capabilities knowledge, the designed perception system should automatically select the best subset of sensors and their sensing modalities that will allow the perception and interpretation of the environment. Then, based on reflectance and emittance theoretical models, the sensor data are fused to extract the physical and geometrical surface properties of the environment surface slope, dielectric constant, temperature and roughness. The theoretical concepts, the design and first results of the multisensor perception system are presented.

On a trajectory tracking problem for nonlinear control systems
93A13166
CHEN, GUANRONG (Houston Univ., TX) In: IEEE Conference on Decision and Control, 30th, Brighton, United Kingdom, Dec. 11-13, 1991, Proceedings. Vol. 3 (A93-13001 02-63). New York, Institute of Electrical and Electronics Engineers, Inc., 1991, p. 2435-2440. Research supported by Univ. of Houston.
An approach for studying typical point-to-point trajectory tracking problems for nonlinear control systems that possess a global linearization is proposed. The trajectory constraints include both the inequality and the equality (interpolatory) types. For purposes of theoretical analysis, system-behavior understanding, and controller design, a minimum control-energy criterion for the linearized system is used. Under this optimality criterion, a characterization result for describing all the possible solutions of such trajectory tracking problems is established. Moreover, the general structure is found in explicit closed-form for these solutions. The research is motivated by a specific example of robotic trajectory planning. Some computer simulation graphs on the robotic trajectory planning problem are included.

Repeatable generalized inverse control strategies for kinematically redundant manipulators
93A13165
ROBERTS, RODNEY G.; MACIEJEWSKI, ANTHONY A. (Purdue Univ., West Lafayette, IN) In: IEEE Conference on Decision and Control, 30th, Brighton, United Kingdom, Dec. 11-13, 1991, Proceedings. Vol. 3 (A93-13001 02-63). New York, Institute of Electrical and Electronics Engineers, Inc., 1991, p. 2428-2434. Research supported by NEC Corp. and TRW, Inc.
The issue of generating a repeatable control strategy which possesses the desirable physical properties of a particular generalized inverse is addressed. This is done by first characterizing repeatable strategies using othonormal basis functions to describe the null space of these transformations. The optimal repeatable inverse is then obtained by projecting the null space of the desired inverse, in an integral norm sense, from the set of all inverses spanned by the selected basis functions. This technique is illustrated for a planar, three-degree-of-freedom manipulator.

An automated collision-avoidance motion planner among moving objects or machines
93A13164
WU, C. H.; FRETER, K.; LEE, D. T.; HWANG, K. S. (Northwestern Univ., Evanston, IL) In: IEEE Conference on Decision and Control, 30th, Brighton, United Kingdom, Dec. 11-13, 1991, Proceedings. Vol. 3 (A93-13001 02-63). New York, Institute of Electrical and Electronics Engineers, Inc., 1991, p. 2422-2427.
An automated motion planner is proposed for coordinating collision-free motions among dynamic moving objects or machines in a 3-D space. Based on the concept of modified path-velocity decomposition, an algorithm is proposed for evaluating the performance of different motion strategies. As a result, the motion planner will coordinate collision-free motions for multiple uncontrollable/controllable objects moving in a shared environment. A dynamic object can also be a multibody object such as a robot. The applicability of the proposed approach is demonstrated through two examples. The results show that multiple controllable and uncontrollable

machines can work together in an industrial environment by efficiently avoiding collisions.

Collision avoidance in a multiple-robot system using intelligent control and neural networks
93A13008
SHIN, KANG G.; CUI, XIANZHONG (Michigan Univ., Ann Arbor) In: IEEE Conference on Decision and Control, 30th, Brighton, United Kingdom, Dec. 11-13, 1991, Proceedings. Vol. 1 (A93-13001 02-63). New York, Institute of Electrical and Electronics Engineers, Inc., 1991, p. 130-135.
A new hierarchical collision avoidance scheme is proposed to coordinate multiple robots in a common workspace by combining the techniques of intelligent control and neural networks (NNs). The high level in the hierarchy is formed by a knowledge-based coordinator (KBC) and an NN-based predictor, and the low level consists of the robots to be coordinated. The authors state the problem of coordinating multiple robots for collision avoidance and the basic principles of the KBC. The knowledge acquisition and representation of collision detection and avoidance for both cylindrical- and revolute-type robots are discussed. Design of the NN-based predictor and the KBC is summarized. The proposed scheme was tested extensively via simulations for both types of robots, showing promising performance.

Machine learning in motion control
94N70949
SU, RENJENG; KERMICHE, NOUREDDINE In its First Annual Symposium. Volume 1: Plenary Session 15 p (SEE N94-70944 07-66) Avail: CASI HC A03/MF A04
The existing methodologies for robot programming originate primarily from robotic applications to manufacturing, where uncertainties of the robots and their task environment may be minimized by repeated off-line modeling and identification. In space application of robots, however, a higher degree of automation is required for robot programming because of the desire of minimizing the human intervention. We discuss a new paradigm of robotic programming which is based on the concept of machine learning. The goal is to let robots practice tasks by themselves and the operational data are used to automatically improve their motion performance. The underlying mathematical problem is to solve the problem of dynamical inverse by iterative methods. One of the key questions is how to ensure the convergence of the iterative process. There have been a few small steps taken into this important approach to robot programming. We give a representative result on the convergence problem.

Critical issues in robot-human operations during the early phases of the Space Station Program
93N72282
LAUDERBAUGH, L. KEN; KONDRASKE, GEORGE; WALKER, MICHAEL W.; CHANG, KAI-HSIUNG (Rensselaer Polytechnic Inst., Troy, NY.); (Texas Univ., Arlington.); (Michigan Univ., Ann Arbor.) Sponsored by the Universities Space Research Association, Columbia, MD, and California Univ., San Diego, La Jolla, CA Avail: CASI HC A04/MF A01
A multidisciplinary team of engineers and scientists from five universities examined major aspects of safety for the Flight Telerobotic Servicer (FTS) program. The team identified several requirements for safe operation of the FTS. They include an overall monitor (or watchdog) system, a single clear line of control at all times, special modes and sensors that apply when an astronaut is inside the FTS' work envelope, confirmed reporting of current status, and manual modes for testing and emergency situations. Topics discussed include: robot safety - industrial experience; human performance considerations; NASREM telerobot control system; software safety for the FTS; and designing for safety.

Collision avoidance of mobile robots in non-stationary environments
93N71641
KYRIAKOPOULOS, K. J.; SARIDIS, G. N. Avail: CASI HC A03/MF A01
A control strategy for real-time collision avoidance of a mobile robot in an environment containing moving obstacles is proposed. A dynamic model of the robot, the constraints and assumptions are presented. Objects, including the robot, are modelled as convex polyhedra. Collision avoidance is guaranteed if the minimum distance between the robot and the objects is nonzero. A nominal trajectory is assumed to be known from off-line planning. The main idea is to change the velocity along the nominal trajectory so that collisions are avoided. Furthermore, consistency with the nominal plan is desirable. The process is formulated as an optimization problem and a close to optimal solution is obtained. Simulation results verify the value of the proposed strategy.

An efficient minimum distance and collision estimation technique for on-line motion planning of robotic manipulation
93N71638
KYRIAKOPOULOS, K. J.; SARIDIS, G. N. Avail: CASI HC A03/MF A01
In this paper, an efficient method for computing the minimum distance between objects is presented. Objects are assumed to be convex polygons. For every object a coordinate frame is assigned. In the beginning the coordinate frames coincide; when the objects move, their new description can be easily obtained if it is expressed using the relative position and orientation of the coordinate frames. If instead of using the Euclidean norm, metric(1) and metric(infinity) are used to represent the distance, then a linear programming problem is formulated. An off-line plan is assumed to preexist described by two functions: one describing the geometry of the path and the other the motion in time along this trajectory. In this framework, an architecture for

on-line collision estimation and motion planning is outlined.

Planning tasks with an emergent connectionist/ symbolic system
93N71631
MOED, MICHAEL C. Avail: CASI HC A03/ MF A01
Rule based systems for planning abstract robotic tasks often suffer by making rule instantiations which do not achieve the desired rule effects. In many of these instances, general rules fail because a specific instantiation is an exception to the general case, and the resulting plan is faulty. In other instances, the specific instantiation fails to achieve the desired effect due to unmodeled perturbations in the environmental state. To overcome these problems, a probability value can be associated with specific instantiations of general rules which quantitatively describes the likelihood that the specific rule achieves the stated effect. From a given initial state, a feasible plan can be developed that satisfies a stated goal by sequencing rules which have highly probable desired effects. The uncertainty that the plan achieves the stated goal can be computed from the probability of effect of each rule used in the plan. However, since the number of possible instantiations of general rules in a rule store may be excessive, all specific rules cannot be tested thoroughly and maintained in memory with corresponding probability of effect values. Instead, probability of effect values for untested instantiations must somehow be reliably extracted from specific, tested rules. The following problems are discussed: (1) developing a methodology for finding sets of specific rules which have a high probability of achieving a desired effect from a base which contains many general rules and a limited number of specific instantiations of these general rules, and (2) sequencing rules which have a high probability of effect to develop a plan of abstract tasks which achieves a desired goal.

Modeling and planning of distributed robot sensing
93N71602
SMITH, RANDALL C.; CHEESEMAN, PETER C.; NITZAN, DAVID Avail: CASI HC A03
In the work statement of Proposal ECU 81-114R we identified components of our three-year study of distributed sensing: (1) planning and information-gathering; (2) sensor planning; and (3) experimental verification. We have made substantial progress on the components of the statement of work, with most emphasis during the first half of the project centered on component (1), which we perceive as the most difficult. This effort has two general results: (1) development of an analytic method useful in judging the necessity and applicability of a sensing step in providing information for a particular goal; and (2) development of a general-purpose planner which will utilize this analysis tool to select among available sensors and sensing strategies in a given task. These developments of component (1) are reviewed. Component (2), which includes modeling specific sensor types and utilizing expert knowledge in sensor selection, was scheduled to receive emphasis in the second and third years of the project, and our work on it has begun. Component (3) will be addressed at the conclusion of the project in the third year.

The Planning Coordinator (PCOORD) for robust error recovery and dynamic on-line planning of robotic tasks
93N71241
FARAH, J. J.; KELLEY, ROBERT B. Avail: CASI HC A03/MF A01
The Planning Coordinator is a logical extension to the Coordination Level of the Intelligent Machine Model, functioning to provide a heretofore unavailable platform for robust error recovery and dynamic on-line planning by autonomous and semi-autonomous robotic systems. This paper introduces the Planning Coordinator and focuses upon its macrostructure, interfaces, and functional description, with respect to its role as the mechanism whereby an existing robotic system requiring significant human intervention can be made more autonomous, thus becoming more robust.

Development of a control system for a pair of robotic platforms
93N71189
COSENTINO, JAMES L. Avail: CASI HC A05/MF A01
This thesis is a discussion of the development of a control system for a pair of three-degree-of-freedom robotic platforms. The platform system and its computer support are described at both the hardware and the software levels, including a section detailing diagnostics which can be run in the event of specific system errors. The design and implementation of a PID controller for the platforms based on experimentally-determined system dynamics is described. Finally, the tracking performance of each joint controller is examined. A path planner is used to map a smooth trajectory between starting and destination positions, and the controller's tracking ability is observed along this path.

Robot planning, execution, and monitoring in an uncertain environment
93N71181
MUNSON, JOHN H. Presented at the Second IJCAI, London, England, 1-3 Sep. 1971 Sponsored in part by ARPA Avail: CASI HC A03/MF A01
An intelligent robot, operating in an external environment that cannot be fully modeled in the robot's software, must be able to monitor the success of its execution of a previously generated plan. This paper outlines a unified formalism for describing and relating the various functions of a robot operating in such an environment. After exploring the distinction between the external world and the robot's internal model of it, and the distinction between actions that interact with the world and the robot's descriptions

of those actions, we formalize the concepts of a plan and of its execution. Current developments at Stanford Research Institute, and the benchmark idea of an 'ultimate' rational robot, are both analyzed in this framework.

Control of a Cartesian robot
93N70978
FRANKLIN, JUDY; NOYES, TERRI; POCOCK, GERRY In Inst. for Applied FORTH Research, Inc., The Journal of FORTH Application and Research, Volume 1, 1983 p 23-31 (SEE N93-70975 04-61) Avail: Issuing Activity
The work in control applications at the Laboratory for Perceptual Robotics has been directed toward a prototype Cartesian Assembler donated to the laboratory by General Electric of Schenectady, New York. The machine and some of the hardware interfaces are described along with the low level controlling schemes for point-to-point position/velocity control. An emulation of single axis controllers is shown to be an effective control method. Encoder/positional information is the basis of this low level control structure which will later be tailored for use with processors devoted to each axis. High level control issues such as adaptive learning techniques are addressed.

Machine learning for flexible robotics
93N70070
DEJONG, GERALD F. Avail: CASI HC A02/MF A01
Robotic planning, if it is to be successful in real world situations, must find some way to side-step the now well-documented obstacles to classical AI planning. These recent results show that the computational complexity of standard planning is unacceptable even with drastic and untenable simplifying assumptions about the world. The source of complexity in real world robotic domains includes the problems of data uncertainty, large amounts of data to consider, as well as the problem of tractably producing plans according to the given domain rules. Pretending that these complexities do not exist relegates a computer system to a trivialized micro-world with little hope of applications to the real world. The research of this grant has been directed towards dealing with the real world constraints that artificial intelligence robotics systems must address. We have made significant progress on two fronts. The first investigates an integrated approach to planning wherein a classical a priori planner is augmented with reactive abilities. The second thrust of this grant explores a new approach called permissive planning. We have implemented our ideas in the GRASPER system which has capabilities to monitor execution of its plans and to tune its model of the world on failure through use of explicit approximations.

Experience with a task control architecture for mobile robots
93N70023
LIN, LONG-JI; SIMMONS, REID; FEDOR, CHRISTOPHER Avail: CASI HC A03/MF A01
This paper presents a general-purpose architecture for controlling mobile robots, and describes a working mobile manipulator which uses the architecture to operate in a dynamic and uncertain environment. The target of this work is to develop a distributed robot architecture for planning, execution, monitoring, exception handling, and multiple task coordination. We report our progress to date on the architecture development and the performance of the working robot. In particular, we discuss temporal reasoning, execution monitoring, and context-dependent exception handling.

Teleoperation with virtual force feedback
94N20293
ANDERSON, R. J. Presented at the Society of Photo-Optical Instrumentation Engineer's (SPIE) International Symposium on Optical Tools for Manufacturing and Advanced Automation, Boston, MA, 7-10 Sep. 1993 Avail: CASI HC A02/MF A01
In this paper we describe an algorithm for generating virtual forces in a bilateral teleoperator system. The virtual forces are generated from a world model and are used to provide real-time obstacle avoidance and guidance capabilities. The algorithm requires that the slaves tool and every object in the environment be decomposed into convex polyhedral Primitives. Intrusion distance and extraction vectors are then derived at every time step by applying Gilbert's polyhedra distance algorithm, which has been adapted for the task. This information is then used to determine the compression and location of nonlinear virtual spring-dampers whose total force is summed and applied to the manipulator/teleoperator system. Experimental results validate the whole approach, showing that it is possible to compute the algorithm and generate realistic, useful pseudo forces for a bilateral teleoperator system using standard VME bus hardware.

Self-organization via active exploration in robotic applications. Phase 2: Hybrid hardware prototype
94N20212
OEGMEN, HALUK Sponsored by NASA. Lyndon B. Johnson Space Center Avail: CASI HC A04/MF A01
In many environments human-like intelligent behavior is required from robots to assist and/or replace human operators. The purpose of these robots is to reduce human time and effort in various tasks. Thus the robot should be robust and as autonomous as possible in order to eliminate or to keep to a strict minimum its maintenance and external control. Such requirements lead to the following properties: fault tolerance, self organization, and intelligence. A good insight into implementing these properties in a robot can be gained by considering human behavior. In the first phase of this project, a neural network architecture was developed that captures some fundamental aspects of human categorization, habit, novelty, and reinforcement behavior. The model,

called FRONTAL, is a 'cognitive unit' regulating the exploratory behavior of the robot. In the second phase of the project, FRONTAL was interfaced with an off-the-shelf robotic arm and a real-time vision system. The components of this robotic system, a review of FRONTAL, and simulation studies are presented in this report.

Robot skill learning and the effects of basis function choice
94N20135
SCHNEIDER, J. G.; BROWN, C. M. Avail: CASI HC A03/MF A01
We present a computational, constructive theory of tunable, open loop trajectory skills. A skill is a controller whose outputs achieve any task in a space characterized by n parameters, n greater than 1. Throwing a ball at a target is a 3-dimensional task if the target may be anywhere within a 3-dimensional volume. Repetitious pick and place tasks are zero-dimensional, and thus not skills. Skills are performed open loop for speed reasons: we assume the entire command sequence is generated before any feedback can become available. We do not assume prior knowledge of plant or task models, so skills must be at least partly learned. A skill output is a vector of values -- in our work so far it is generated as the sum of a base vector and a weighted change vector whose weight accomplishes the tuning. Learning consists of a search for the best set of base and change vectors. An interpretation process maps skill outputs into sequences of commands for the plant by using basis functions (given a priori in this paper). The basis functions may be arbitrarily complex. We claim that appropriate basis functions can speed up the learning process and overcome the limitations of the linear trajectory tuning algorithm. This report describes a skill learning algorithm and experiments done with various basis functions and control methods for a one-dimensional throwing task. It concludes with a discussion of future work in learning basis functions, higher dimensional tasks, and comparisons against common learning and control algorithms.

Robot navigation in unknown terrains: Introductory survey of non-heuristic algorithms
94N19300
RAO, N. S. V.; KARETI, S.; SHI, WEIMIN; IYENGAR, S. S. (Old Dominion Univ., Norfolk, VA.); (Old Dominion Univ., Norfolk, VA.); (Louisiana State Univ., Baton Rouge.) Avail: CASI HC A04/MF A01
A formal framework for navigating a robot in a geometric terrain through an unknown set of obstacles is considered. Here the terrain model is not known a priori, but the robot is equipped with a sensor system (vision or touch) employed for the purpose of navigation. The focus is restricted to the non-heuristic algorithms which can be theoretically shown to be correct within a given framework of models for the robot, terrain, and sensor system. These formulations, although abstract and simplified compared to real-life scenarios, provide foundations for practical systems by highlighting the underlying critical issues. First, the authors consider the algorithms that are shown to navigate correctly without much consideration given to the performance parameters, such as distance traversed. Second, they consider non-heuristic algorithms that guarantee bounds on the distance traversed or the ratio of the distance traversed to the shortest path length (computed if the terrain model is known). Then they consider the navigation of robots with very limited computational capabilities such as finite automata.

Adaptive path planning: Algorithm and analysis
94N18926
CHEN, PANG C. Presented at the 6th International Symposium of Robotics Research, Pittsburgh, PA, 2 Oct. 1993 Avail: CASI HC A02/MF A01
Path planning has to be fast to support real-time robot programming. Unfortunately, current planning techniques are still too slow to be effective, as they often require several minutes, if not hours of computation. To alleviate this problem, we present a learning algorithm that uses past experience to enhance future performance. The algorithm relies on an existing path planner to provide solutions to difficult tasks. From these solutions, an evolving sparse network of useful subgoals is learned to support faster planning. The algorithm is suitable for both stationary and incrementally-changing environments. To analyze our algorithm, we use a previously developed stochastic model that quantifies experience utility. Using this model, we characterize the situations in which the adaptive planner is useful, and provide quantitative bounds to predict its behavior. The results are demonstrated with problems in manipulator planning. Our algorithm and analysis are sufficiently general that they may also be applied to task planning or other planning domains in which experience is useful.

Survey of collision avoidance and ranging sensors for mobile robots, revision 1
94N18474
EVERETT, H. R.; DEMUTH, D. E.; STITZ, E. H. Avail: CASI HC A08/MF A02
The past few years have brought about a tremendous rise in the envisioned potential of robotic systems and a significant increase in the number of proposed applications. In the nonindustrial arena, numerous programs have evolved, each intending to harness some of this promise in hopes of solving some particular application need. Many of these efforts are government sponsored, aimed at the development of systems for fighting fires, handling ammunition, transporting materials, conducting underwater search and inspection operations, and patrolling warehouses and storage areas, etc. Many of the resulting prototypes, which were initially perceived as logical extensions of the traditional industrial robotic scenarios, have met with unexpected difficulty due to an insufficient supporting technology base. This document provides some

basic background on the various noncontact distance measurement techniques available, with related discussion of implementation in the acoustical, optical, and electromagnetic portions of the energy spectrum. An overview of candidate systems, both commercially available and under development, is provided, followed by a brief summary of research currently underway in support of the collision avoidance and noncontact ranging needs of a mobile robot.

Flexible integration of path-planning capabilities
94N18463
STOBIE, IAIN C.; TAMBE, MILIND; ROSENBLOOM, PAUL S. Avail: Issuing Activity (Defense Technical Information Center (DTIC))
Robots pursuing complex goals must plan paths according to several criteria of quality including shortness, safety, speed, and planning time. Many sources and kinds of knowledge, such as maps, procedures and perception, may be available or required. Both the quality criteria and sources of knowledge may vary widely over time, and in general they will interact. One approach to address this problem is to express all criteria and goals numerically in a single weighted graph, and then to search this graph to determine a path. Since this is problematic with symbolic or uncertain data and interacting criteria, we propose that what is needed instead is an integration of many kinds of planning capabilities. We describe a hybrid approach to integration, based on experiments with building simulated mobile robots using Soar, an integrated problem-solving and learning system. For flexibility, we have implemented a combination of internal planning, reactive capabilities, and specialized tools. We illustrate how these components can complement each other's limitations and produce plans which integrate geometric and task knowledge.

Autonomous neural network controllers for adaptive material handling
94N18331
KOTTAS, JAMES; KUPERSTEIN, MICHAEL Avail: CASI HC A03/MF A01
For robots to be more useful in flexible manufacturing and service applications, the controllers must be able to handle more variable environments. On at least two levels, conventional methods in robot control have problems dealing with high variability. At the current level, conventional dynamic control formulations cannot deal effectively with the highly variable dynamic inertial interactions between multijointed robots and payloads. At the task level, the initial and final positions for materials to be moved may change slightly but unexpectedly. We have developed autonomous neural network controllers that learn from their own experience to deal with environmental variability at these levels.

Magnetostrictive actuators for human sensory feedback
94N17841
BRIMHALL, OWEN D.; KNOWLTON, DANIEL; CURTIN, HOWARD R. Avail: CASI HC A03/MF A01
The development of actuators with enhanced capabilities is critical to the achievement of sensory feedback systems for intuitive, real time human operation of telerobotic systems. The objective of this research project was to demonstrate feasibility of new actuators using active materials which will enhance the capabilities of dexterous, exoskeletal feedback systems for telerobotic applications. In phase 1, feasibility of several novel Terfenol-D magnetostrictive actuators were demonstrated. Several prototype actuators were fabricated and tested, including resistive single axis brakes, resistive multiaxis (ball) brake joints, and linear motors. The new actuators are relatively efficient, responsive, small and exert high forces. The actuators provide proportional forces and are easily interfaced with digital electronics. Several of the actuators were integrated into a simple demonstration board. Phase 2 will pursue advanced development of proportional force resistive brake actuators and active linear motion actuators.

Integrating reactive and deliberative planning for agents
94N17201
BLYTHE, JIM; REILLY, W. S. Avail: Issuing Activity (Defense Technical Information Center (DTIC))
Autonomous agents that respond intelligently in dynamic, complex environments need to be both reactive and deliberative. Reactive systems have traditionally fared better than deliberative planners in such environments, but are often hard to code and inflexible. To fill in some of these gaps, we propose a hybrid system that exploits the strengths of both reactive and deliberative systems. We demonstrate how out system controls a simulated household robot and compare our system to a purely reactive one in this domain. We also look at a number of relevant issues in anytime planning.

An object-oriented program specification for a mobile robot motion control language
94N16986
GRIM, CARL J. Avail: CASI HC A06/MF A02
The Yamabico Research Group at the Naval Postgraduate School is actively pursuing improvements in design and implementation of applications for it's family of autonomous mobile robots. This paper describes a new high level language for controlling the Yamabico-11, surnamed OOPS-MML (Object-Oriented Program Specification for a Mobile robot Motion control Language). Conceptual goals included a user friendly, high level interface coupled with a very abstract, efficient and compartmentalized architecture to employ a path planning and tracking application developed at NPS. The result is a robust and flexible robot control system that is intended to be implemented and employed onboard the Yamabico-11.

Contextually dependent control strategies for manipulation
94N16580
POOK, POLLY K.; BALLARD, DANA H. Avail: CASI HC A03/MF A01
Traditional analytic robotics defines grasping by knowing the task geometry and the forces acting on the manipulator precisely. This method is particularly important for non-compliant manipulators with few degrees of freedom, such as a parallel jaw gripper, that overconstrain the solution space. In contrast, the advent of anthropomorphic, high degree-of-freedom grippers allows us to use closed-loop strategies that depend heavily on the task context but do not require precise positioning knowledge. To demonstrate, a robotic hand flips a plastic egg, using the finger joint tendon tensions as the the sole control signal. The manipulator is a compliant, sixteen degree-of-freedom, Utah/MIT hand mounted on a Puma 760 arm. The completion of each subtask, such as picking up the spatula, finding the pan, and sliding the spatula under the egg, is detected by sensing when the tensions of the hand tendons pass a threshold. Beyond this use of tendon tensions and the approximate starting position of the spatula and pan, no model of the task is constructed. The routine is found to be robust to different spatulas and to changes in the location and orientation of the spatula, egg, and table, with some exceptions. The egg-flipping example relies on interpreting fluctuating tension values within a known temporal sequence of actions. For instance, knowing when the manipulator is trying to touch the pan with the spatula provides the context to interpret changes in tendon tensions. Given the success of this task, we go on to propose a method for analyzing the temporal sensory output for tasks that have not been previously segmented. This method suggests a means for automatically generating robust force control programs to perform previously teleoperated manipulation tasks.

The ESA telescience program
94N16073
NAJA, G. In National Research Council Canada, Proceedings of the Second Workshop on Microgravity Experimentation 7 p (SEE N94-16071 03-29) Avail: Issuing Activity (National Research Council, Publication Sales and Distribution, Montreal Road, Ottawa, Ontario, K1A OR6 Canada)
In the Columbus space station Attached Laboratory, there will be 40 experiment racks but less than two crew members available to tend them, meaning that experiment operations cannot be permanently performed by the crew. The Columbus Free Flyer will be a completely automated laboratory, serviced periodically by astronauts. To facilitate the running of experiments in the Columbus facilities, the telescience concept will be used extensively. Telescience provides ground-based users with interactive and transparent access to their on-orbit experiments. Data such as telemetry and video are received by the user, who then can react by sending telecommands to activate mechanisms or robotic systems to operate the experiment. To validate the telescience concept, to promote it, and to train telescience users, a testbed has been developed and installed. The testbed has integrated five pilot experiments operated through a user workstation. The testbed has also been used in an operational simulation of long-duration space missions. A flight test of a telescience experiment investigating Marangoni convection was performed in Nov. 1989 onboard a sounding rocket with complete success.

Hidden Markov model approach to skill learning and its application to telerobotics
94N15502
YANG, JIE; XU, YANGSHENG; CHEN, C. S. Avail: CASI HC A03/MF A01
In this paper, we discuss the problem of how human skill can be represented as a parametric model using a hidden Markov model (HMM), and how a HMM-based skill model can be used to learn human skill. HMM is feasible to characterize two stochastic processes--measurable action and immeasurable mental states--which are involved in the skill learning. We formulated the learning problem as a multi-dimensional HMM and developed a programming system which serves as a skill learning testbed for a variety of applications. Based on 'the most likely performance' criterion, we can select the best action sequence from all previously measured action data by modeling the skill as HMM. This selection process can be updated in real-time by feeding new action data and modifying HMM parameters. We address the implementation of the proposed method in a teleoperation-controlled space robot. An operator specifies the control command by a hand controller for the task of exchanging Orbit Replaceable Unit, and the robot learns the operation skill by selecting the sequence which represents the most likely performance of the operator. The skill is learned in Cartesian space, joint space, and velocity domain. The experimental results demonstrate the feasibility of the proposed method in learning human skill and teleoperation control. The learning is significant in eliminating sluggish motion and correcting the motion command which the operator mistakenly generates.

Robot programming, natural computation and conceptual graphs
94N13539
KAPITANOVSKY, ALEX Avail: Issuing Activity (Tel-Aviv Univ., Exact Sciences Library, Ramat Aviv 69978, Israel)
A method is developed for robot program synthesis. Currently, the programming of a robot task is one of the major hurdles of robot application. The automation of robot program synthesis will ease industrial application of robots. In order to develop a support system for robot programming, it is proposed to consider the natural information processing by humans during synthesis and interpretation of robotic programs and then to construct an approxi-

mate conceptual model of the dynamically changing real world which is involved. Such a model must be suitable (i.e., representable and executable) for efficient computer processing. This approach enables the proposed system to provide a means for automated (knowledge guided) conversion of a user's request, expressed in a natural language, to the appropriate conceptual model of the required task. This model incorporates the information necessary for understanding, planning, and sensory-guided performance of the required robotic task. In Part A, the overall framework of the system is defined, together with the first phase of an assembly program synthesis: request specification, planning of the valid assembly sequences and determination of the required sources. Part B concerns the final phase of a robot program synthesis and its interpretation in changing conditions. A case study is presented, to illustrate this approach on the large family of multi-axisymmetric components.

Application of intelligently adaptable structure and robot to large space structure
94N13277
SENDA, KEI; MUROTSU, YOSHISADA In NASDA, The Second Workshop on Deployment and Assembly Experiment of Large Space Structure on Orbit p 47-53 (SEE N94-13268 02-12) Avail: CASI HC A02/MF A01
The status of the research on applying intelligently a adaptable structure and robot to a large space structure is presented. The following items are described: (1) the selected research subjects; (2) the present status of the research on FFR (Free Flying Robot) including formulation concerning FFR, inertial parameter identification and manipulator orbit plan for controlling the attitude of rigid FFR, study on controlling of FFR with flexible manipulator applying virtual rigid manipulator concept, hardware experiments using a model with one or two of two link solid manipulator, and the one with a two link flexible manipulator; (3) the intelligently adaptable structure including actuator layout; (4) optimum attitude utilization as a docking mechanism; and (5) control of flexible space structure.

Experiments in mobile robot navigation and range imaging
94N12598
JONES, J. P.; DORUM, O. H.; ANDERSEN, C. S.; JACOBSEN, S. V.; JENSEN, M. S.; KIERKEBY, N. O. S.; KRISTENSEN, S. (Norges Tekniske Hoegskole, Trondheim.); (Aalborg Univ., Denmark.); (Aalborg Univ., Denmark.); (Aalborg Univ., Denmark.); (Aalborg Univ., Denmark.); (Aalborg Univ., Denmark.) Presented at the 8th Scandanavian Conference on Image Analysis, Tromso, Norway, 25-28 May 1993 Avail: CASI HC A03/MF A01
This paper describes some experiments in sensor-based mobile robot navigation conducted at Oak Ridge National Laboratory over the past several years. Two implemented systems are described. One uses a laser range camera as the sole sensor. The other uses, in addition, an array of sonars and a stereo vision system. We discuss a communication system for heterogeneous LAN-connected multiprocessor systems, useful in reasonably large development projects such as these. We also describe some work on the estimation of curvature in range images which introduces a new variational principle motivated by minimization of the change of curvature. Application of this principle is shown to produce results which are more desirable in some respects than those obtained using standard quadratic variation.

The rational behavior model: A multi-paradigm, tri-level software architecture for the control of autonomous vehicles
94N11874
BYRNES, RONALD B., JR. Avail: CASI HC A14/MF A03
There is currently a very strong interest among researchers in the fields of artificial intelligence and robotics in finding more effective means of linking high level symbolic computations relating to mission planning and control for autonomous vehicles to low level vehicle control software. The diversity exhibited by the many processes involved in such control has resulted in a number of proposals for a general software architecture intended to provide an efficient yet flexible framework for the organization and interaction of relevant software components. The Rational Behavior Model (RBM) has been developed with these requirements in mind and consists of three levels, called the Strategic, the Tactical, and the Execution levels, respectively. Each level reflects computations supporting the solution to the global control problem based on different abstraction mechanisms. The unique contribution of the RBM architecture is the idea of specifying different programming paradigms to realize each software level. Specifically, RBM uses rule-based programming for the Strategic level, thereby permitting field reconfiguration of missions by a mission specialist without reprogramming at lower levels. The Tactical level realizes vehicle behaviors as the methods of software objects programmed in an object-based language such as Ada. These behaviors are initiated by rule satisfaction at the Strategic level, thereby rationalizing their interaction. The Execution level is programmed in any imperative language capable of supporting efficient execution of real-time control of the underlying vehicle hardware.

Supervised autonomous control, shared control, and teleoperation for space servicing
94N11577
BACKES, PAUL G. In NASA. Johnson Space Center, Sixth Annual Workshop on Space Operations Applications and Research (SOAR 1992), Volume 2 p 720-731 (SEE N94-11527 01-99) Sponsored by NASA, Washington Avail: CASI HC A03/MF A03
A local-remote telerobot system for single- and dual-arm supervised autonomy, shared control, and

teleoperation has been demonstrated. The system is composed of two distinct parts: the local site, where the operator resides; and the remote site, where the robots reside. The system could be further separated into dual local sites communicating with a common remote site. This is valuable for potential space missions where a space based robotic system may be controlled either by a space based operator or by a ground based operator. Also, multiple modes of control integrated into a common system are valuable for satisfying different servicing scenarios. The remote site single arm control system is described, and its parameterization for different supervised autonomous control, shared control, and tele-operation tasks are given. Experimental results are also given for selected tasks. The tasks include compliant grasping, orbital replacement unit changeout, bolt seating and turning, electronics card removal and insertion, and door opening.

The development of an interactive synthesis tool for intelligent controllers of modular, reconfigurable robots
94N10898
AMBROSE, CATHERINE GLAUBER Avail: Univ. Microfilms Order No. DA9309115
Intelligent controller design for modular, reconfigurable robot architectures was investigated. In robotic systems available today, the controller is the main limiting factor for enhanced performance. Numerous researchers are studying new controller architectures to allow for the implementation of advanced software, but few have targeted their research at reconfigurable designs. Focus was on the development of a modular controller architecture that can be reconfigured to meet the changing needs of new manipulators and new tasks. The dissertation work was divided into two parallel lines of research. First, a road map assessing the required technology for an intelligent controller was created. A complete model of robotic manipulators was developed which included the arm dynamics and the dynamics of the joint actuator systems. This model was used to determine the desired update rate for command signals from the robot controller. Second, a synthesis package was developed on a Silicon Graphics workstation to simulate controller architectures. This package allows the user to assemble computer components and select controller algorithms, and then evaluates the effectiveness of the design. Bottlenecks are easily identified and improved architectures can be rapidly created. This synthesis package was used to underscore the issues discussed in the road map.

Telerobot control system
94N10670
BACKES, PAUL G.; TSO, KAM S. (Jet Propulsion Lab., California Inst. of Tech., Pasadena.); (Jet Propulsion Lab., California Inst. of Tech., Pasadena.) Filed 9 May 1991 Supersedes N91-32509 (29 - 24, p 4028) Avail: US Patent and Trademark Office
This invention relates to an operator interface for controlling a telerobot to perform tasks in a poorly modeled environment and/or within unplanned scenarios. The telerobot control system includes a remote robot manipulator linked to an operator interface. The operator interface includes a setup terminal, simulation terminal, and execution terminal for the control of the graphics simulator and local robot actuator as well as the remote robot actuator. These terminals may be combined in a single terminal. Complex tasks are developed from sequential combinations of parameterized task primitives and recorded teleoperations, and are tested by execution on a graphics simulator and/or local robot actuator, together with adjustable time delays. The novel features of this invention include the shared and supervisory control of the remote robot manipulator via operator interface by pretested complex tasks sequences based on sequences of parameterized task primitives combined with further teleoperation and run-time binding of parameters based on task context.

Telerobotic control of a mobile coordinated robotic server
94N10345
LEE, GORDON Avail: CASI HC A04/MF A01
The annual report on telerobotic control of a mobile coordinated robotic server is presented. The goal of this effort is to develop advanced control methods for flexible space manipulator systems. As such, an adaptive fuzzy logic controller was developed in which model structure as well as parameter constraints are not required for compensation. The work builds upon previous work on fuzzy logic controllers. Fuzzy logic controllers have been growing in importance in the field of automatic feedback control. Hardware controllers using fuzzy logic have become available as an alternative to the traditional PID controllers. Software has also been introduced to aid in the development of fuzzy logic rule-bases. The advantages of using fuzzy logic controllers include the ability to merge the experience and intuition of expert operators into the rule-base and that a model of the system is not required to construct the controller. A drawback of the classical fuzzy logic controller, however, is the many parameters needed to be turned off-line prior to application in the closed-loop. In this report, an adaptive fuzzy logic controller is developed requiring no system model or model structure. The rule-base is defined to approximate a state-feedback controller while a second fuzzy logic algorithm varies, on-line, parameters of the defining controller. Results indicate the approach is viable for on-line adaptive control of systems when the model is too complex or uncertain for application of other more classical control techniques.

Position and force control of a vehicle with two or more steerable drive wheels
94N10269
REISTER, D. B.; UNSEREN, M. A. Avail: CASI

HC A03/MF A01
When a vehicle with two or more steerable drive wheels is traveling in a circle, the motion of the wheels is constrained. The wheel translational velocity divided by the radius to the center of rotation must be the same for all wheels. When the drive wheels are controlled independently using position control, the motion of the wheels may violate the constraints and the wheels may slip. Consequently, substantial errors can occur in the orientation of the vehicle. A vehicle with N drive wheels has (N - 1) constraints and one degree of freedom. We have developed a new approach to the control of a vehicle with N steerable drive wheels. The novel aspect of our approach is the use of force control. To control the vehicle, we have one degree of freedom for the position on the circle and (N - 1) forces that can be used to reduce errors. Recently, Kankaanranta and Koivo developed a control architecture that allows the force and position degrees of freedom to be decoupled. In the work of Kankaanranta and Koivo, the force is an exogenous input. We have made the force endogenous by defining the force in terms of the errors in satisfying the rigid body kinematic constraints. We have applied the control architecture to the HERMIES-3 robot and have measured a dramatic reduction in error (more than a factor of 20) compared to motions without force control.

Real-time qualitative reasoning for telerobotic systems
93N32116
PIN, EANCOIS G. In NASA. Lyndon B. Johnson Space Center, The Sixth Annual Workshop on Space Operations Applications and Research (SOAR 1992) p 173 (SEE N93-32097 12-99)
Avail: CASI HC A01/MF A04
This paper discusses the sensor-based telerobotic driving of a car in a-priori unknown environments using 'human-like' reasoning schemes implemented on custom-designed VLSI fuzzy inferencing boards. These boards use the Fuzzy Set theoretic framework to allow very vast (30 kHz) processing of full sets of information that are expressed in qualitative form using membership functions. The sensor-based and fuzzy inferencing system was incorporated on an outdoor test-bed platform to investigate two control modes for driving a car on the basis of very sparse and imprecise range data. In the first mode, the car navigates fully autonomously to a goal specified by the operator, while in the second mode, the system acts as a telerobotic driver's aid providing the driver with linguistic (fuzzy) commands to turn left or right, speed up, slow down, stop, or back up depending on the obstacles perceived by the sensors. Indoor and outdoor experiments with both modes of control are described in which the system uses only three acoustic range (sonar) sensor channels to perceive the environment. Sample results are presented that illustrate the feasibility of developing autonomous navigation modules and robust, safety-enhancing driver's aids for telerobotic systems using the new fuzzy inferencing VLSI hardware and 'human-like' reasoning schemes.

TeleOperator/TelePresence System (TOPS) Concept Verification Model (CVM) development
93N32112
SHIMAMOTO, MIKE S. In NASA. Lyndon B. Johnson Space Center, The Sixth Annual Workshop on Space Operations Applications and Research (SOAR 1992) p 149-155 (SEE N93-32097 12-99)
Avail: CASI HC A02/MF A04
The development of an anthropomorphic, undersea manipulator system, the TeleOperator/telePresence System (TOPS) Concept Verification Model (CVM) is described. The TOPS system's design philosophy, which results from NRaD's experience in undersea vehicles and manipulator systems development and operations, is presented. The TOPS design approach, task teams, manipulator, and vision system development and results, conclusions, and recommendations are presented.

Air Force construction automation/robotics
93N32110
NEASE, A. D.; ALEXANDER, E. F. In NASA. Lyndon B. Johnson Space Center, The Sixth Annual Workshop on Space Operations Applications and Research (SOAR 1992) p 121-130 (SEE N93-32097 12-99) Avail: CASI HC A02/MF A04
The Air Force has several missions which generate unique requirements that are being met through the development of construction robotic technology. One especially important mission will be the conduct of Department of Defense (DOD) space activities. Space operations and other missions place construction/repair equipment operators in dangerous environments and potentially harmful situations. Additionally, force reductions require that human resources be leveraged to the maximum extent possible, and more stringent construction repair requirements push for increased automation. To solve these problems, the U.S. Air Force is undertaking a research and development effort at Tyndall AFB, FL, to develop robotic construction/repair equipment. This development effort involves the following technologies: teleoperation, telerobotics, construction operations (excavation, grading, leveling, tool change), robotic vehicle communications, vehicle navigation, mission/vehicle task control architecture, and associated computing environment. The ultimate goal is the fielding of a robotic repair capability operating at the level of supervised autonomy. This paper will discuss current and planned efforts in space construction/repair, explosive ordnance disposal, hazardous waste cleanup, and fire fighting.

Interactive and cooperative sensing and control for advanced teleoperation
93N32108
LEE, SUKHAN In NASA. Lyndon B. Johnson Space Center, The Sixth Annual Workshop on Space Operations Applications and Research (SOAR 1992) p 104-115 (SEE N93-32097 12-99)

Avail: CASI HC A03/MF A04
This paper presents the paradigm of interactive and cooperative sensing and control as a fundamental mechanism of integrating and fusing the strengths of man and machine for advanced teleoperation. The interactive and cooperative sensing and control is considered as an extended and generalized form of traded and shared control. The emphasis of interactive and cooperative sensing and control is given to the distribution of mutually nonexclusive subtasks to man and machine, the interactive invocation of subtasks under the man/machine symbiotic relationship, and the fusion of information and decisionmaking between man and machine according to their confidence measures. The proposed interactive and cooperative sensing and control system is composed of such major functional blocks as the logical sensor system, the sensor-based local autonomy, the virtual environment formation, and the cooperative decision-making between man and machine. The Sensing-Knowledge-Command (SKC) fusion network is proposed as a fundamental architecture for implementing cooperative and interactive sensing and control. Simulation results are shown.

Integration of advanced teleoperation technologies for control of space robots
93N32107
STAGNARO, MICHAEL J. In its The Sixth Annual Workshop on Space Operations Applications and Research (SOAR 1992) p 94-103 (SEE N93-32097 12-99) Avail: CASI HC A02/MF A04
Teleoperated robots require one or more humans to control actuators, mechanisms, and other robot equipment given feedback from onboard sensors. To accomplish this task, the human or humans require some form of control station. Desirable features of such a control station include operation by a single human, comfort, and natural human interfaces (visual, audio, motion, tactile, etc.). These interfaces should work to maximize performance of the human/robot system by streamlining the link between human brain and robot equipment. This paper describes development of a control station testbed with the characteristics described above. Initially, this testbed will be used to control two teleoperated robots. Features of the robots include anthropomorphic mechanisms, slaving to the testbed, and delivery of sensory feedback to the testbed. The testbed will make use of technologies such as helmet mounted displays, voice recognition, and exoskeleton masters. It will allow tor integration and testing of emerging telepresence technologies along with techniques for coping with control link time delays. Systems developed from this testbed could be applied to ground control of space based robots. During man-tended operations, the Space Station Freedom may benefit from ground control of IVA or EVA robots with science or maintenance tasks. Planetary exploration may also find advanced teleoperation systems to be very useful.

Man-machine cooperation in advanced teleoperation
93N32106
FIORINI, PAOLO; DAS, HARI; LEE, SUKHAN In NASA. Lyndon B. Johnson Space Center, The Sixth Annual Workshop on Space Operations Applications and Research (SOAR 1992) p 87-93 (SEE N93-32097 12-99) Avail: CASI HC A02/MF A04
Teleoperation experiments at JPL have shown that advanced features in a telerobotic system are a necessary condition for good results, but that they are not sufficient to assure consistently good performance by the operators. Two or three operators are normally used during training and experiments to maintain the desired performance. An alternative to this multi-operator control station is a man-machine interface embedding computer programs that can perform some of the operator's functions. In this paper we present our first experiments with these concepts, in which we focused on the areas of real-time task monitoring and interactive path planning. In the first case, when performing a known task, the operator has an automatic aid for setting control parameters and camera views. In the second case, an interactive path planner will rank different path alternatives so that the operator will make the correct control decision. The monitoring function has been implemented with a neural network doing the real-time task segmentation. The interactive path planner was implemented for redundant manipulators to specify arm configurations across the desired path and satisfy geometric, task, and performance constraints.

Supervisory autonomous local-remote control system design: Near-term and far-term applications
93N32100
ZIMMERMAN, WAYNE; BACKES, PAUL In NASA. Lyndon B. Johnson Space Center, The Sixth Annual Workshop on Space Operations Applications and Research (SOAR 1992) p 28-40 (SEE N93-32097 12-99) Avail: CASI HC A03/MF A04
The JPL Supervisory Telerobotics Laboratory (STELER) has developed a unique local-remote robot control architecture which enables management of intermittent bus latencies and communication delays such as those expected for ground-remote operation of Space Station robotic systems via the TDRSS communication platform. At the local site, the operator updates the work site world model using stereo video feedback and a model overlay/fitting algorithm which outputs the location and orientation of the object in free space. That information is relayed to the robot User Macro Interface (UMI) to enable programming of the robot control macros. The operator can then employ either manual teleoperation, shared control, or supervised autonomous control to manipulate the object under any degree of time-delay. The remote site performs the closed loop force/torque control, task monitoring, and reflex action. This paper describes the STELER local-remote robot control system, and further describes the near-term planned Space Station applications, along with potential far-term ap-

plications such as telescience, autonomous docking, and Lunar/Mars rovers.

A vision system planner for increasing the autonomy of the Extravehicular Activity Helper/Retriever
93N31844
MAGEE, MICHAEL Avail: CASI HC A04/ MF A01
The Extravehicular Activity Retriever (EVAR) is a robotic device currently being developed by the Automation and Robotics Division at the NASA Johnson Space Center to support activities in the neighborhood of the Space Shuttle or Space Station Freedom. As the name implies, the Retriever's primary function will be to provide the capability to retrieve tools and equipment or other objects which have become detached from the spacecraft, but it will also be able to rescue a crew member who may have become inadvertently de-tethered. Later goals will include cooperative operations between a crew member and the Retriever such as fetching a tool that is required for servicing or maintenance operations. This paper documents a preliminary design for a Vision System Planner (VSP) for the EVAR that is capable of achieving visual objectives provided to it by a high level task planner. Typical commands which the task planner might issue to the VSP relate to object recognition, object location determination, and obstacle detection. Upon receiving a command from the task planner, the VSP then plans a sequence of actions to achieve the specified objective using a model-based reasoning approach. This sequence may involve choosing an appropriate sensor, selecting an algorithm to process the data, reorienting the sensor, adjusting the effective resolution of the image using lens zooming capability, and/or requesting the task planner to reposition the EVAR to obtain a different view of the object. An initial version of the Vision System Planner which realizes the above capabilities using simulated images has been implemented and tested. The remaining sections describe the architecture and capabilities of the VSP and its relationship to the high level task planner. In addition, typical plans that are generated to achieve visual goals for various scenarios are discussed. Specific topics to be addressed will include object search strategies, repositioning of the EVAR to improve the quality of information obtained from the sensors, and complementary usage of the sensors and redundant capabilities.

Supervised autonomy in telerobotics
93N30326
BURTNYK, N.; BASRAN, J. (Ottawa Univ., Ontario.) In Engineering Inst. of Canada, Canadian Conference on Electrical and Computer Engineering, Volumes 1 and 2 7 p (SEE N93-30215 11-31) Avail: Engineering Inst. of Canada, 2050 rue Mansfield, Suite 700, Montreal, Quebec H3A 1Z2 Canada
Advanced autonomous robots are envisaged for applications in harsh, demanding or dangerous environments such as nuclear, underwater operations, space, mining and tunneling, civil engineering and construction, etc. A major challenge in telerobotics development is to incorporate the robot's capability for autonomous operation wherever possible. A supervisory control concept for exploiting autonomous functionality in an unstructured environment is presented. Through an effective man-machine dialogue, the operator uses human perceptual and planning abilities to assist the robot in acquiring a model of its environment. Once this structure is acquired, the operator instructs the robot on how to perform a task as a sequence of actions based on generic skills. A discussion of the technical solutions that are essential to implement this concept and the results of a study to develop a robot operating under supervised autonomy are presented.

A functional system architecture for fully autonomous robot
93N30311
KALAYCIOGLU, S. In Engineering Inst. of Canada, Canadian Conference on Electrical and Computer Engineering, Volumes 1 and 2 4 p (SEE N93-30215 11-31) Avail: Engineering Inst. of Canada, 2050 rue Mansfield, Suite 700, Montreal, Quebec H3A 1Z2 Canada
The Mobile Servicing System (MSS) Autonomous Robotics Program intends to define and plan the development of technologies required to provide a supervised autonomous operation capability for the Special Purpose Dexterous Manipulator (SPDM) on the MSS. The operational functions for the SPDM to perform the required tasks, both in fully autonomous or supervised modes, are identified. Functional decomposition is performed using a graphics oriented methodology called Structural Analysis Design Technique. This process defines the functional architecture of the system, the types of data required to support its functionality, and the control processes that need to be emplaced. On the basis of the functional decomposition, a technology breakdown structure is also developed. A preliminary estimate of the status and maturity of each relevant technology is made, based on this technology breakdown. The developed functional hierarchy is found to be very effective for a robotic system with any level of autonomy. Moreover, this hierarchy can easily be applied to an existing very low level autonomous system and can provide a smooth transition towards a higher degree of autonomy. The effectiveness of the developed functional hierarchy will also play a very significant role both in the system design as well as in the development of the control hierarchy.

Input relegation control for gross motion of a kinematically redundant manipulator
93N30210
UNSEREN, M. A. Presented at the 1993 Institute of Electrical and Electronics Engineers/Robotics Society of Japan (IEERSJ) International Conference on Intelligent Robots and Systems (IROS), Yokohama, Japan, 26-30 Jul. 1993 Avail: CASI HC

A03/MF A01
This paper proposes a method for resolving the kinematic redundancy of a serial link manipulator moving in a three-dimensional workspace. The underspecified problem of solving for the joint velocities based on the classical kinematic velocity model is transformed into a well-specified problem. This is accomplished by augmenting the original model with additional equations which relate a new vector variable quantifying the redundant degrees of freedom (DOF) to the joint velocities. The resulting augmented system yields a well specified solution for the joint velocities. Methods for selecting the redundant DOF quantifying variable and the transformation matrix relating it to the joint velocities are presented so as to obtain a minimum Euclidean norm solution for the joint velocities. The results obtained from experimentally implementing the proposed scheme on the CESARM research manipulator are presented.

The planning coordinator: A design architecture for autonomous error recovery and on-line planning of intelligent tasks
93N30039
FARAH, JEFFREY J. Avail: CASI HC A07/ MF A02
Developing a robust, task level, error recovery and on-line planning architecture is an open research area. There is previously published work on both error recovery and on-line planning; however, none incorporates error recovery and on-line planning into one integrated platform. The integration of these two functionalities requires an architecture that possesses the following characteristics. The architecture must provide for the inclusion of new information without the destruction of existing information. The architecture must provide for the relating of pieces of information, old and new, to one another in a non-trivial rather than trivial manner (e.g., object one is related to object two under the following constraints, versus, yes, they are related; no, they are not related). Finally, the architecture must be not only a stand alone architecture, but also one that can be easily integrated as a supplement to some existing architecture. This thesis proposal addresses architectural development. Its intent is to integrate error recovery and on-line planning onto a single, integrated, multi-processor platform. This intelligent x-autonomous platform, called the Planning Coordinator, will be used initially to supplement existing x-autonomous systems and eventually replace them.

Application of sensors to the control of robotic systems
93N30012
HARRIGAN, R. W. Presented at the 50th Anniversary Spring Conference on Experimental Mechanics, Dearborn, MI, 9 Jun. 1993 Avail: CASI HC A02/MF A01
Hazardous operations which in the past have been completed by technicians are under increased scrutiny due to high costs and low productivity associated with providing protective clothing and environments. As a result, remote systems are needed to accomplish many hazardous materials handling tasks such as the clean up of waste sites in which the exposure of personnel to radiation, chemical, explosive, and other hazardous constituents is unacceptable. Traditional remote manual operations have proven to have very low productivity when compared with unencumbered humans. Computer models augmented by sensing and structured, modular computing environments are proving to be effective in automating many unstructured hazardous tasks.

Planning collision free paths for two cooperating robots using a divide-and-conquer C-space traversal heuristic
93N29771
WEAVER, JOHNATHAN M. Avail: CASI HC A08/MF A02
A method was developed to plan feasible and obstacle-avoiding paths for two spatial robots working cooperatively in a known static environment. Cooperating spatial robots as referred to herein are robots which work in 6D task space while simultaneously grasping and manipulating a common, rigid payload. The approach is configuration space (c-space) based and performs selective rather than exhaustive c-space mapping. No expensive precomputations are required. A novel, divide-and-conquer type of heuristic is used to guide the selective mapping process. The heuristic does not involve any robot, environment, or task specific assumptions. A technique was also developed which enables solution of the cooperating redundant robot path planning problem without requiring the use of inverse kinematics for a redundant robot. The path planning strategy involves first attempting to traverse along the configuration space vector from the start point towards the goal point. If an unsafe region is encountered, an intermediate via point is identified by conducting a systematic search in the hyperplane orthogonal to and bisecting the unsafe region of the vector. This process is repeatedly applied until a solution to the global path planning problem is obtained. The basic concept behind this strategy is that better local decisions at the beginning of the trouble region may be made if a possible way around the 'center' of the trouble region is known. Thus, rather than attempting paths which look promising locally (at the beginning of a trouble region) but which may not yield overall results, the heuristic attempts local strategies that appear promising for circumventing the unsafe region.

An autonomous vision-based mobile robot
93N29082
BAUMGARTNER, ERIC THOMAS Avail: Univ. Microfilms Order No. DA9308220
This dissertation describes estimation and control methods for use in the development of an autonomous mobile robot for structured environments. The navigation of the mobile robot is based on precise

estimates of the position and orientation of the robot within its environment. The extended Kalman filter algorithm is used to combine information from the robot's drive wheels with periodic observations of small, wall-mounted, visual cues to produce the precise position and orientation estimates. The visual cues are reliably detected by at least one video camera mounted on the mobile robot. Typical position estimates are accurate to within one inch. A path tracking algorithm is also developed to follow desired reference paths which are taught by a human operator. Because of the time-independence of the tracking algorithm, the speed that the vehicle travels along the reference path is specified independent from the tracking algorithm. The estimation and control methods have been applied successfully to two experimental vehicle systems. Finally, an analysis of the linearized closed-loop control system is performed to study the behavior and the stability of the system as a function of various control parameters.

Robotics and artificial intelligence for hazardous environments
93N29047
SPELT, P. F. Presented at the 17th Congress of Investigation Cientifica Universidad Interamericana De Puerto Rico, San Juan, Puerto Rico, 11-12 Feb. 1993 Avail: CASI HC A03/MF A01
In our technological society, hazardous materials including toxic chemicals, flammable, explosive, and radioactive substances, and biological agents, are used and handled routinely. Each year, many workers who handle these substances are accidently contaminated, in some cases resulting in injury, death, or chronic disabilities. If these hazardous materials could be handled remotely, either with a teleoperated robot (operated by a worker in a safe location) or by an autonomous robot, then human suffering and economic costs of accidental exposures could be dramatically reduced. At present, it is still difficult for commercial robotic technology to completely replace humans involved in performing complex work tasks in hazardous environments. The robotics efforts at the Center for Engineering Systems Advanced Research represent a significant effort at contributing to the advancement of robotics for use in hazardous environments. While this effort is very broad-based, ranging from dextrous manipulation to mobility and integrated sensing, focus is on machine learning and the high-level decision making needed for autonomous robotics.

Intelligent robots for planetary exploration and construction
93N27980
ALBUS, JAMES S. In Arizona Univ., Proceedings of the Lunar Materials Technology Symposium 15 p (SEE N93-27956 10-91) Avail: CASI HC A03/ MF A03
Robots capable of practical applications in planetary exploration and construction will require realtime sensory-interactive goal-directed control systems. A reference model architecture based on the NIST Real-time Control System (RCS) for real-time intelligent control systems is suggested. RCS partitions the control problem into four basic elements: behavior generation (or task decomposition), world modeling, sensory processing, and value judgment. It clusters these elements into computational nodes that have responsibility for specific subsystems, and arranges these nodes in hierarchical layers such that each layer has characteristic functionality and timing. Planetary exploration robots should have mobility systems that can safely maneuver over rough surfaces at high speeds. Walking machines and wheeled vehicles with dynamic suspensions are candidates. The technology of sensing and sensory processing has progressed to the point where real-time autonomous path planning and obstacle avoidance behavior is feasible. Map-based navigation systems will support long-range mobility goals and plans. Planetary construction robots must have high strength-to-weight ratios for lifting and positioning tools and materials in six degrees-of-freedom over large working volumes. A new generation of cable-suspended Stewart platform devices and inflatable structures are suggested for lifting and positioning materials and structures, as well as for excavation, grading, and manipulating a variety of tools and construction machinery.

Architecture of autonomous systems
93N26047
DIKSHIT, PIYUSH; GUIMARAES, KATIA; RAMAMURTHY, MAYA; AGRAWALA, ASHOK; LARSEN, RONALD L. Avail: CASI HC A04/MF A01
Automation of Space Station functions and activities, particularly those involving robotic capabilities with interactive or supervisory human control, is a complex, multi-disciplinary systems design problem. A wide variety of applications using autonomous control can be found in the literature, but none of them seem to address the problem in general. All of them are designed with a specific application in mind. In this report, an abstract model is described which unifies the key concepts underlying the design of automated systems such as those studied by the aerospace contractors. The model has been kept as general as possible. The attempt is to capture all the key components of autonomous systems. With a little effort, it should be possible to map the functions of any specific autonomous system application to the model presented here.

Real-time construction and rendering of three-dimensional occupancy maps
93N25516
JONES, J. P. Presented at the 11th Society of Photo-Optical Instrumentation Engineering Applications of Artificial Intelligence, Orlando, FL, 12-16 Apr. 1993 Avail: CASI HC A02/MF A01
This paper describes a preliminary sensory system for real-time sensor-based navigation in a three-dimensional, dynamic environment. Data from a

laser range camera are processed on an iWarp parallel computer to create a 3D occupancy map. This map is rendered using raytracing. The construction and rendering consume less than 800 milliseconds.

A global path planning approach for redundant manipulators
93N24656
SEEREERAM, SANJEEV; WEN, J. Avail: CASI HC A04/MF A01
A new approach for global path planning of redundant manipulators is proposed. It poses the path planning problem as a finite time nonlinear control problem. The solution is found by a Newton-Raphson type algorithm. This technique is capable of handling various goal task descriptions as well as incorporating both joint and task space constraints. The algorithm has shown promising preliminary results in planning joint path sequences for 3R and 4R planar robots to meet Cartesian tip tracking and goal endpoint planning. It is robust with respect to local path planning problems such as singularity considerations and local minimum problems. Repetitive joint path solutions for cyclic end-effector tasks are also generated. Eventual goals of this work include implementation on full spatial robots, as well as provision of an interface for supervisory input to aid in path planning for more complex problems.

Transformational planning of reactive behavior
93N24270
MCDERMOTT, DREW Avail: CASI HC A04/MF A01
Reactive plans are plans that include steps for sensing the world and coping with the data so obtained. The application of AI planning techniques to plans of this sort in a simple simulated world is investigated. To achieve fast reaction times, it is assumed that the agent starts with a default reactive plan, while the planner attempts to improve it by applying plan transformations, thus searching through the space of transformed plans. When the planner has what it believes to be a better plan, it swaps the new plan into the agent's controller. The plans are written in a reactive language that allows for this kind of swapping. The language allows for concurrency, and hence, truly 'nonlinear' plans. The planner evaluates plans by projecting them, that is, generating scenarios for how execution might go. The resulting projections give estimates of plan values, but also provide clues to how the plan might be improved. These clues are unearthed by critics that go through the scenario sets, checking how the world state and the agent state evolved. The critics suggest plan transformations with associated estimates of how much they will improve the plan. Plan transformations must be able to edit code trees in such a way that the changes are orthogonal and reversible whenever possible. The system was tested by comparing the performance of the agent with and without planning. Preliminary results allow us to conclude that the planner can be fast and directed enough to generate improved plans in a timely fashion, and that the controller can often cope with a sudden shift of plan.

Kinematics and dynamics of robotic systems with multiple closed loops
93N24218
ZHANG, CHANG-DE Avail: Univ. Microfilms Order No. DA9238371
The kinematics and dynamics of robotic systems with multiple closed loops, such as Stewart platforms, walking machines, and hybrid manipulators, are studied. In the study of kinematics, focus is on the closed-form solutions of the forward position analysis of different parallel systems. A closed-form solution means that the solution is expressed as a polynomial in one variable. If the order of the polynomial is less than or equal to four, the solution has analytical closed-form. First, the conditions of obtaining analytical closed-form solutions are studied. For a Stewart platform, the condition is found to be that one rotational degree of freedom of the output link is decoupled from the other five. Based on this condition, a class of Stewart platforms which has analytical closed-form solution is formulated. Conditions of analytical closed-form solution for other parallel systems are also studied. Closed-form solutions of forward kinematics for walking machines and multi-fingered grippers are then studied. For a parallel system with three three-degree-of-freedom subchains, there are 84 possible ways to select six independent joints among nine joints. These 84 ways can be classified into three categories: Category 3:3:0, Category 3:2:1, and Category 2:2:2. It is shown that the first category has no solutions; the solutions of the second category have analytical closed-form; and the solutions of the last category are higher order polynomials. The study is then extended to a nearly general Stewart platform. The solution is a 20th order polynomial and the Stewart platform has a maximum of 40 possible configurations. Also, the study is extended to a new class of hybrid manipulators which consists of two serially connected parallel mechanisms. In the study of dynamics, a computationally efficient method for inverse dynamics of manipulators based on the virtual work principle is developed. Although this method is comparable with the recursive Newton-Euler method for serial manipulators, its advantage is more noteworthy when applied to parallel systems. An approach of inverse dynamics of a walking machine is also developed, which includes inverse dynamic modeling, foot force distribution, and joint force/torque allocation. A new approach is then proposed to determine the foot distribution of planar walking gaits based on two optimum criteria. A computational scheme is then developed to determine the joint force/torque allocation, on the basis of the virtual work principle. As an illustration, the inverse dynamic modeling of a quadruped with pantograph legs is derived. The

inverse dynamics of this quadruped walking in different wave gaits is then studied.

Trajectory control of an articulated robot with a parallel drive arm based on splines under tension
93N24184
YI, SEUNG-JONG Avail: Univ. Microfilms Order No. DA9238369
Today's industrial robots controlled by mini/micro computers are basically simple positioning devices. The positioning accuracy depends on the mathematical description of the robot configuration to place the end-effector at the desired position and orientation within the workspace and on following the specified path which requires the trajectory planner. In addition, the consideration of joint velocity, acceleration, and jerk trajectories are essential for trajectory planning of industrial robots to obtain smooth operation. The newly designed 6 DOF articulated robot with a parallel drive arm mechanism which permits the joint actuators to be placed in the same horizontal line to reduce the arm inertia and to increase load capacity and stiffness is selected. First, the forward kinematic and inverse kinematic problems are examined. The forward kinematic equations are successfully derived based on Denavit-Hartenberg notation with independent joint angle constraints. The inverse kinematic problems are solved using the arm-wrist partitioned approach with independent joint angle constraints. Three types of curve fitting methods used in trajectory planning, i.e., certain degree polynomial functions, cubic spline functions, and cubic spline functions under tension, are compared to select the best possible method to satisfy both smooth joint trajectories and positioning accuracy for a robot trajectory planner. Cubic spline functions under tension is the method selected for the new trajectory planner. This method is implemented for a 6 DOF articulated robot with a parallel drive arm mechanism to improve the smoothness of the joint trajectories and the positioning accuracy of the manipulator. Also, this approach is compared with existing trajectory planners, 4-3-4 polynomials and cubic spline functions, via circular arc motion simulations. The new trajectory planner using cubic spline functions under tension is implemented into the microprocessor based robot controller and motors to produce combined arc and straight-line motion. The simulation and experiment show interesting results by demonstrating smooth motion in both acceleration and jerk and significant improvements of positioning accuracy in trajectory planning.

Perception, scene reconstruction and world modeling for unmanned underwater vehicles
93N23443
MOORE, JOHN, JR. Workshop held in Cambridge, MA, 26-27 Jan. 1993 Sponsored by National Sea Grant Coll. Program, Silver Spring, MD Avail: CASI HC A03/MF A01
The workshop addresses the sensory and perceptual issues associated with the operation of intelligent systems in an underwater environment. Topics range from low-level processing, including novel hardware approaches, through the high-level techniques for combining data from multiple sensors and different sensing modalities. Presentations primarily focus on developments in computer algorithms for sensory data processing and representation of an unmanned underwater vehicle's environment, and include: perceptual strategies; physics-based sensing and world modeling; techniques for scene reconstruction; merging data over extended periods of time; target acquisition, recognition, and classification; and the trade-offs between global modeling and task-relative perception.

Autonomus obstacle avoidance using visual fixation and looming
93N23442
JOARDER, KUNAL; RAVIV, DANIEL Sponsored by National Inst. of Standards and Technology, Gaithersburg, MD Avail: CASI HC A03/MF A01
The paper describes a vision-based method for avoiding obstacles using the concepts of visual looming and fixating motion. Visual looming refers to the expansion of images of objects in the retina. Usually, this is due to the decreasing distance between the observer and the object. An increasing looming value signifies an increasing threat of collision with the object. The visual task of avoiding collision can be further simplified by purposive control of visual fixation at the objects in front of the moving camera. Using these two basic concepts, real time obstacle avoidance in a tight perception-action loop is implemented. Three-dimensional space in front of the camera is divided into zones with various degrees of looming-based threat of collision. For each obstacle seen by a fixating camera, looming and its time derivative are calculated directly from the 2D image. Depending on the threat posed by an obstacle, a course change is dictated. This looming based approach is simple, independent of the size of the 3D object and its range, and involves simple quantitative measurements. Results pertinent to a camera on a robot arm navigating between obstacles are presented.

Sensor-based whole-arm obstacle avoidance utilizing ASIC technology
93N22819
WINTENBERG, A. L.; ERICSON, M. N.; BABCOCK, S. M.; ARMSTRONG, G. A.; BRITTON, C. L., JR.; BUTLER, P. L.; HAMEL, W. R.; NEWPORT, D. F. (Tennessee Univ., Knoxville.) Presented at the 5th Topical Meeting on Robotics and Remote Systems, Knoxville, TN, 26-29 Apr. 1993 Avail: CASI HC A03/MF A01
Operation of manipulator systems in poorly defined work environments often presents a significant hazard to both the robotic assembly and the environment. In applications relating to the Environmental Restoration and Waste Management (ER&WM) Program, many of the environments are considered hazardous, both, in the structure and composition of

the environment. Use of a sensing system that provides information to the manipulator control unit regarding obstacles in close proximity will provide protection against collisions. A hierarchical design and implementation of a whole-arm obstacle avoidance system is presented. The system is based on capacitive sensors configured as bracelets for proximity sensing. Each bracelet contains a number of sensor nodes and a processor for sensor node control and readout, and communications with a higher level host, common to all bracelets. The host controls the entire sensing network and communicates proximity information to the manipulator controller. The overall architecture of this system is discussed with detail on the individual system modules. Details of an application specific integrated circuit (ASIC) designed to implement the sensor node electronics are presented. Justifications for the general measurement methods and associated implementation are discussed. Additionally, the current state of development including measured data is presented.

Advanced telerobotic control using neural networks
93N22364
PAP, ROBERT M.; ATKINS, MARK; COX, CHADWICK; GLOVER, CHARLES; KISSEL, RALPH; SAEKS, RICHARD (Accurate Automation Corp., Chattanooga, TN.); (Accurate Automation Corp., Chattanooga, TN.); (Accurate Automation Corp., Chattanooga, TN.); (Tennessee State Univ., Nashville.); (Accurate Automation Corp., Chattanooga, TN.) In NASA. Johnson Space Center, Proceedings of the Third International Workshop on Neural Networks and Fuzzy Logic, Volume 1 p 93-94 (SEE N93-22351 08-63) Sponsored in part by ONR and NSF Avail: CASI HC A01/MF A03
Accurate Automation is designing and developing adaptive decentralized joint controllers using neural networks. We are then implementing these in hardware for the Marshall Space Flight Center PFMA as well as to be usable for the Remote Manipulator System (RMS) robot arm. Our design is being realized in hardware after completion of the software simulation. This is implemented using a Functional-Link neural network.

A fault-tolerant intelligent robotic control system
93N22159
MARZWELL, NEVILLE I.; TSO, KAM SING (SoHaR, Inc., Beverly Hills, CA.) In NASA, Washington, Technology 2002: The Third National Technology Transfer Conference and Exposition, Volume 2 p 101-110 (SEE N93-22149 08-99) Avail: CASI HC A02/MF A04
This paper describes the concept, design, and features of a fault-tolerant intelligent robotic control system being developed for space and commercial applications that require high dependability. The comprehensive strategy integrates system level hardware/software fault tolerance with task level handling of uncertainties and unexpected events for robotic control. The underlying architecture for system level fault tolerance is the distributed recovery block which protects against application software, system software, hardware, and network failures. Task level fault tolerance provisions are implemented in a knowledge-based system which utilizes advanced automation techniques such as rule-based and model-based reasoning to monitor, diagnose, and recover from unexpected events. The two level design provides tolerance of two or more faults occurring serially at any level of command, control, sensing, or actuation. The potential benefits of such a fault tolerant robotic control system include: (1) a minimized potential for damage to humans, the work site, and the robot itself; (2) continuous operation with a minimum of uncommanded motion in the presence of failures; and (3) more reliable autonomous operation providing increased efficiency in the execution of robotic tasks and decreased demand on human operators for controlling and monitoring the robotic servicing routines.

Avoiding space robot collisions utilizing the NASGSFC tri-mode skin sensor
93N21812
PRINZ, F. B. S.; MAHALINGAM, S. Avail: CASI HC A03/MF A01
A capacitance based proximity sensor, the 'Capaciflector' (Vranish 92), has been developed at the Goddard Space Flight Center of NASA. We had investigated the use of this sensor for avoiding and maneuvering around unexpected objects (Mahalingam 92). The approach developed there would help in executing collision-free gross motions. Another important aspect of robot motion planning is fine motion planning. Let us classify manipulator robot motion planning into two groups at the task level: gross motion planning and fine motion planning. We use the term 'gross planning' where the major degrees of freedom of the robot execute large motions, for example, the motion of a robot in a pick and place type operation. We use the term 'fine motion' to indicate motions of the robot where the large dofs do not move much, and move far less than the mirror dofs, such as in inserting a peg in a hole. In this report we describe our experiments and experiences in this area.

Reliable fusion of control and sensing in intelligent machines
93N21371
MCINROY, JOHN E. Avail: CASI HC A08/MF A02
Although robotics research has produced a wealth of sophisticated control and sensing algorithms, very little research has been aimed at reliably combining these control and sensing strategies so that a specific task can be executed. To improve the reliability of robotic systems, analytic techniques are developed for calculating the probability that a particular combination of control and sensing algorithms will satisfy the required specifications. The probability can then be used to assess the reliability of the design. An entropy formulation is first used to

quickly eliminate designs not capable of meeting the specifications. Next, a framework for analyzing reliability based on the first order second moment methods of structural engineering is proposed. To ensure performance over an interval of time, lower bounds on the reliability of meeting a set of quadratic specifications with a Gaussian discrete time invariant control system are derived. A case study analyzing visual positioning in robotic system is considered. The reliability of meeting timing and positioning specifications in the presence of camera pixel truncation, forward and inverse kinematic errors, and Gaussian joint measurement noise is determined. This information is used to select a visual sensing strategy, a kinematic algorithm, and a discrete compensator capable of accomplishing the desired task. Simulation results using PUMA 560 kinematic and dynamic characteristics are presented.

Case-based reasoning for real-time problem solving
93N19865
HAMMOND, KRISTIAN; OWENS, CHRISTOPHER; MARTIN, CHARLES Avail: CASI HC A03/MF A01
This document summarizes the University of Chicago Artificial Intelligence laboratory's work on applying case-based methods to intelligent real-time problem solving. An approach to problem solving involving the storage, retrieval, adaptation, and re-use of successful strategies is outlined. The report describes work on an overall control architecture, on methodological issues in the development of representation vocabularies, and on memory organization for efficient storage and retrieval of cases. Work on six projects is described including work on robot planning, the dynamic repair of transportation schedules, multi-agent cooperative planning, case-based design, and active perception. The result of this work is a model of planning and execution that handles the complexity and instability of a dynamic, real-time environment by making use of known plans stored in memory.

Cooperation of mobile robots for accident scene inspection
93N19478
BYRNE, R. H.; HARRINGTON, J. Presented at the ISRAM 1992: 4th International Symposium on Robotics and Manufacturing, Sante Fe, NM, 11-13 Nov. 1992 Avail: CASI HC A02/MF A01
A telerobotic system demonstration was developed for the Department of Energy's Accident Response group to highlight the applications of telerobotic vehicles to accident site inspection. The proof-of-principle system employs two mobile robots, Dixie and RAYBOT, to inspect a simulated accident site. Both robots are controlled serially from a single driving station, allowing an operator to take advantage of having multiple robots at the scene. The telerobotic system is described and some of the advantages of having more than one robot present are discussed. Future plans for the system are also presented.

Nonlinear robust controller design for multi-robot systems with unknown payloads
93N19462
SONG, Y. D.; ANDERSON, J. N.; HOMAIFAR, A.; LAI, H. Y. (Tennessee Technological Univ., Cookeville.) In its The Center for Aerospace Research: A NASA Center of Excellence at North Carolina Agricultural and Technical State University 16 p (SEE N93-19452 06-80) Avail: CASI HC A03/MF A03
This work is concerned with the control problem of a multi-robot system handling a payload with unknown mass properties. Force constraints at the grasp points are considered. Robust control schemes are proposed that cope with the model uncertainty and achieve asymptotic path tracking. To deal with the force constraints, a strategy for optimally sharing the task is suggested. This strategy basically consists of two steps. The first detects the robots that need help and the second arranges that help. It is shown that the overall system is not only robust to uncertain payload parameters, but also satisfies the force constraints.

A safety-based decision making architecture for autonomous systems
93N19362
MUSTO, JOSEPH C.; LAUDERBAUGH, L. K. Avail: CASI HC A03/MF A01
Engineering systems designed specifically for space applications often exhibit a high level of autonomy in the control and decision-making architecture. As the level of autonomy increases, more emphasis must be placed on assimilating the safety functions normally executed at the hardware level or by human supervisors into the control architecture of the system. The development of a decision-making structure which utilizes information on system safety is detailed. A quantitative measure of system safety, called the safety self-information, is defined. This measure is analogous to the reliability self-information defined by McInroy and Saridis, but includes weighting of task constraints to provide a measure of both reliability and cost. An example is presented in which the safety self-information is used as a decision criterion in a mobile robot controller. The safety self-information is shown to be consistent with the entropy-based Theory of Intelligent Machines defined by Saridis.

Teleprogramming: Remote site robot task execution
93N19046
LINDSAY, THOMAS STEWART Avail: Univ. Microfilms Order No. DA9235172
This dissertation describes a remote site robot workcell for teleoperation with communication delays on the order of 20 seconds. In these situations, direct teleoperation becomes impossible due to the delays in visual and force feedback. Teleprogramming has been developed in order to overcome this problem. An integral part of teleprogramming is a semi-autonomous remote site robot system. The remote system is composed of a

robot manipulator, sensors, controlling computer, and manipulator tools. The constraints on the remote site system and the amount of autonomy needed are defined partially by the teleprogramming system and partially by the needs of the remote system. Development of the remote site system for teleprogramming evokes some pertinent research issues: low level manipulator control, semi-autonomous command execution, and remote site tool usage. Low level manipulator control is based on a hybrid control scheme using wrist-based sensory feedback. Implementation of this control is presented and problems related to controlling the manipulator in an arbitrary frame are investigated. High level commands are executed at the remote site in small autonomous steps. Implementation of tolerance checks and guarded moves are presented, including error detection and the detection of motion termination conditions in a partially known environment. Power tools introduce redundant degrees of freedom into the manipulator/tool system. To control this redundant system, the tool is actively controlled in its natural degree of freedom and the corresponding degree of freedom in the manipulator becomes passive. Feedback for the manipulator/tool system is supplied by the wrist-based sensor. Two examples of sensing and control for tools are presented. This research has resulted in the development of a remote site system for teleprogramming. The remote system, however, is both time-delay and input independent. The characteristics of the system, including the compliance, flexibility, and semi-autonomity, are useful to a wide variety of robotics applications, including manufacturing and direct teleoperation.

Voice control of a dual-arm telerobot
93N19044
HABERLEIN, ROBERT ARTHUR Avail: Univ. Microfilms Order No. DA9238647
This investigation explores voice control of a dual-arm telerobot. A literature review of voice control, voice technology and work measurements is conducted. This review includes a discussion of important voice technology topics, a survey of commercial voice equipment, and a study of industrial and vocational work measurement techniques. A voice control system is created for two Kraft GRIPS Master-Slave telerobotic manipulators. This system is based upon the concept of distributed computer control using inexpensive PC-AT computers that exchange information according to special communication and command protocols. The voice control system consists of four separate sub-systems; a Camera Sub-system that controls a motorized camera mount, a Teach Pendant Sub-system that emulates two standard Termiflex teach pendants, a Switch Sub-system that controls the Kraft Master switches, and a Voice Sub-system that accepts the operator's vocal commands and broadcasts digitally-recorded messages. The Voice Sub-system utilizes a Votan VPC-2100 recognition board and a TI-Speech synthesis board. The vocal commands are organized into a hierarchical structure based upon the fire-and-forget control scheme. A visual display of the vocal command status is also detailed. In order to measure the effect of the voice control system upon the work performance of the telerobot, a formal experimental plan is described using twenty-four untrained operators divided into a voice group and a control group. Each group performs an experimental taskset using modified peg-in-hole vocational rehabilitation assessment test equipment. The experimental taskset consists of eight separate subtasks that exercise each of the four voice control sub-systems. The times to complete the subtasks are recorded to score each group's work performance. A split-plot ANOVA of the performance scores reveals significant group improvements in both the mean performance and the performance variance for those tasks which involve control of the telerobot and its peripheral systems. No significant group differences are found for those subtasks which chiefly involve the dexterity of the telerobotic Slaves.

ORCCAD: Towards an open robot controller computer aided design system
93N18519
JOUBERT, ANTOINE; SIMON, DANIEL (Ecole Nationale Superieure des Mines, Valbonne, France) Sponsored in part by Commission of the European Communities Avail: CASI HC A03/MF A01
The implementation of robotics tasks via various robot controller architectures using the ORCCAD system is addressed. The development of new robotic tasks deals with many different techniques and scientific fields. Automatic control is involved in control laws analysis while computer science tools are used to produce efficient real time programs. Following the development of a full example, a methodology for the design of new robotics tasks and a review of the tools to be used at each step of the task development, are given.

Composite video and graphics display for camera viewing systems in robotics and teleoperation
93N18284
DINER, DANIEL B.; VENEMA, STEVEN C. (Jet Propulsion Lab., California Inst. of Tech., Pasadena.); (Jet Propulsion Lab., California Inst. of Tech., Pasadena.) Filed 17 Jun. 1991 Supersedes N92-10126 (30 - 1, p 25) Avail: US Patent and Trademark Office
A system for real-time video image display for robotics or remote-vehicle teleoperation is described that has at least one robot arm or remotely operated vehicle controlled by an operator through hand-controllers, and one or more television cameras and optional lighting element. The system has at least one television monitor for display of a television image from a selected camera and the ability to select one of the cameras for image display. Graphics are generated with icons of cameras and lighting elements for display surrounding the television image to provide the operator information on: the location and orientation of each camera and lighting

element; the region of illumination of each lighting element; the viewed region and range of focus of each camera; which camera is currently selected for image display for each monitor; and when the controller coordinate for said robot arms or remotely operated vehicles have been transformed to correspond to coordinates of a selected or nonselected camera.

Design requirements for force reflecting master controllers
93N18035
SRINIVASSEN, M. Avail: CASI HC A03/MF A01
The design criteria imposed by the capabilities of the human user on the design of force reflecting controllers for hands and arms are discussed. This paper contains four sections. First, we present a framework of questions regarding human capabilities. Second, a subset of the criteria is selected as the critical task set. Third, values for this task set are either presented or engineering experiments for determining the values are given. Lastly, the relationship between the critical task set and the engineering specifications for the machine are given. The framework discusses in a broad way all of the kinesthetic, kinematic, and tactile capabilities of the human hand and arm. A machine which met or exceeded all of these capabilities would present a true virtual reality interface. Many of these criteria cannot be met with current technologies. Therefore, the critical sensing/actuation dimensions for performing a set of tasks on a task board must be determined. We present a hypothesized set of criteria based on experience and the literature, and discuss some simple experiments that can be used to clarify the selection. For all of the capabilities, we present values that are available in the literature. The source of each value is referenced, and the experiment is briefly summarized and critiqued. For critical capabilities with unknown values, we have designed some engineering experiments to determine the values. In the design of the machine, only a subset of the human capability criteria are important in determining engineering design specifications. For instance, force threshold without any bias load determines the maximum reflected force that the mechanism can apply in free motion mode. This in turn determines the friction that can be tolerated in the design. We present the important engineering design parameters, and show how these can be determined from the human capabilities.

Automatic tuning for a teleoperated arm controller
93N17481
KRESS, R. L.; JANSEN, J. F. Presented at the 31st IEEE Conference on Decision and Control, Tuscon, AZ, 16-18 Dec. 1992 Avail: CASI HC A01/ MF A01
This paper addresses the problem of determining an optimal set of gains for a controller for a teleoperated arm. Specifically, an automatic tuning technique was applied and investigated for tuning an independent-joint proportional-derivative controller for a teleoperated manipulator. The Hooke and Jeeves method is used in conjunction with a one-dimensional search routine in the tuning algorithm. The algorithm was used to optimize gains for a two-link teleoperator simulation and the results of several optimizations were used to determine the best form for an input trajectory and cost function. The desired joint angle trajectory is taken from low-pass filtered step inputs with randomly generated magnitudes, which vary at a predetermined interval. Both positive and negative angles are generated, but they are constrained to lie within the manipulator work space. It was determined that the cost function should be based on tracking error, peak position error over the entire desired path, overshoot, actuator torque bounds, and gain limits. The optimized gains obtained from the simulation were applied to an actual teleoperator and some improvement was seen.

Implementation of robotic force control with position accommodation
93N16663
RYAN, MICHAEL J. Avail: CASI HC A05/ MF A02
As the need for robotic manipulation in fields such as manufacturing and telerobotics increases, so does the need for effective methods of controlling the interaction forces between the manipulators and their environment. Position Accommodation (PA) is a form of robotic force control where the nominal path of the manipulator is modified in response to forces and torques sensed at the tool-tip of the manipulator. The response is tailored such that the manipulator emulates a mechanical impedance to its environment. PA falls under the category of position-based robotic force control, and may be viewed as a form of Impedance Control. The practical implementations are explored of PA into an 18 degree-of-freedom robotic testbed consisting of two PUMA 560 arms mounted on two 3 DOF positioning platforms. Single and dual-arm architectures for PA are presented along with some experimental results. Characteristics of position-based force control are discussed, along with some of the limitations of PA.

A telerobotic digital controller system
93N16658
BROWN, RICHARD J. Avail: CASI HC A08/ MF A02
This system is a network of joint mounted dual axes digital servo-controllers (DDSC), providing control of various joints and end effectors of different robotic systems. This report provides description of and user required information for the Digital Controller System Network (DSCN) and, in particular, the DDSC, Model DDSC-2, developed to perform the controller functions. The DDSC can control 3 phase brushless or brush type DC motors, requiring up to 8 amps. Only four wires, two for power and 2 for serial communication, are required, except for local sensor and motor connections. This highly

capable, very flexible, programmable servo-controller, contained on a single, compact printed circuit board measuring only 4.5 x 5.1 inches, is applicable to control systems of all types from sub-arc second precision pointing to control of robotic joints and end effectors. This document concentrates on the robotic applications for the DDSC.

Telerobotic control of a mobile coordinated robotic server
93N16387
LEE, GORDON Avail: CASI HC A05/MF A02
Results from the Master's Degree Thesis of Mr. Robert Stanley, a graduate student supervised by the principal investigator on this project is reported. The goal of this effort is to develop advanced control methods for flexible space manipulator systems. As such, a fuzzy logic controller has been developed in which model structure as well as parameter constraints are not required for compensation. A general rule base is formulated using quantized linguistic terms; it is then augmented to a traditional integral control. The resulting hybrid fuzzy controller stabilizes the structure over a broad range of uncertainties, including unknown initial conditions. An off-line tuning approach using phase portraits gives further insight into the algorithm. The approach was applied to a three-degree-of-freedom manipulator system - the prototype of the coordinated flexible manipulator system currently being designed and built at North Carolina State University.

Stereo vision controlled bilateral telerobotic remote assembly station
93N16120
DEWITT, ROBERT L. Avail: CASI HC A04/MF A01
The objective of this project was to develop a bilateral six degree-of-freedom telerobotic component assembly station utilizing remote stereo vision assisted control. The component assembly station consists of two Unimation Puma 260 robot arms and their associated controls, two Panasonic miniature camera systems, and an air compressor. The operator controls the assembly station remotely via kinematically similar master controllers. A Zenith 386 personal computer acts as an interface and system control between the human operator's controls and the Val II computer controlling the arms. A series of tasks, ranging in complexity and difficulty, was utilized to assess and demonstrate the performance of the complete system.

Knowledge-based planning
93N15812
MCDERMOTT, DREW; HAGER, GREGORY
Avail: CASI HC A02/MF A01
The goal of our project is to study planning for autonomous agents with imperfect sensors in a dynamic world. Such agents must confront several problems: (1) how to synchronize plan execution with plan refinement; (2) how to generate reasonable plans quickly for complex goals, and improve them later; (3) how to trade off sensor-processing time against the quality of information; and (4) how to learn the structure of the environment as plan execution proceeds.

SMART: A modular architecture for robotics and teleoperation
93N15385
ANDERSON, R. J. Presented at the ISRAM 1992: Fourth International Symposium on Robotics and Manufacturing, Santa Fe, NM, 11-13 Nov. 1992
Avail: CASI HC A02/MF A01
This paper introduces SMART: Sandia National Laboratory's Modular Architecture for Robotics and Teleoperation. SMART is designed to integrate the different slave devices (e.g., large hydraulic arms, mobile manipulators, and gantry robots), sensors (e.g., ultra-sonic sensors and force sensors), and input devices, (e.g., track ball, force-reflecting master, and autonomous trajectory generators) required for waste management and environmental restoration tasks. The modular architecture allows for rapid synthesis of complex telerobotic systems. This paper introduces some sample modules and illustrates how the modules can be connected to achieve telerobotic behaviors. Examples include autonomous control, impedance control, and enhanced bilateral teleoperation.

Adaptive control of a manipulator in cartesian space
93N15308
MURTY, VENKATAESH V.; SHUNMUGAM, M. S. In CASA-RI/SME, Proceedings of the International Conference on CACAM and AMT. Volume 3: IFIP/Robotics: International Sessions on Robots and Assembly 5 p (SEE N93-15298 04-61) Avail: CASI HC A01/MF A02
A cartesian based nonlinear adaptive controller is presented for the trajectory control of a robot manipulator. The stability of the control formulation is proved using Lyapunov's second method. The unknown parameters of the system, as well as the variable payload are estimated on-line, tending the system errors to zero. This formulation, unlike other adaptive controllers present in the literature, neither makes any ad hoc linearization of the nonlinear equations nor requires the inversion of the inertia matrix. It also does not require the measurement of acceleration and the conversion of path planning specifications from cartesian space to joint space. Trajectory tracking, with unknown parameter values and variable payload, is simulated to show the effectiveness of the proposed adaptive control algorithm.

Coordinated motion control of a two-hand assembly system
93N15301
BIDAUD, P.; FONTAINE, D.; BOUDIN, F.; GUINOT, J. C. In CASA-RI/SME, Proceedings of the International Conference on CACAM and AMT. Volume 3: IFIP/Robotics: International Sessions on Robots and Assembly 4 p (SEE N93-15298 04-61)

Avail: CASI HC A01/MF A02
This paper presents the implementation of an original cooperating system for precise assembly operations. The whole mechanical architecture consists of a conventional manipulator robot and a micro-manipulator setting in parallel. The micro-manipulator used is a manipulator-gripper in a left-hand configuration. The mechanism of the manipulator-gripper was designed to perform active or passive fine compliant motions. A hybrid force/position control structure is used to control the grasped object motions in operational space. A real-time distributed computer system has been developed for coordinated-motion control. For complex assembly tasks, automatic fine motion strategies are obtained by a rule-based expert system.

Methodology for robot capability and performance characterization: The basis for robot task planning
93N15300
RUBINOVITZ, JACOB; WYSK, RICHARD A. (Pennsylvania State Univ., University Park.) In CASA-RI/SME, Proceedings of the International Conference on CACAM and AMT. Volume 3: IFIP/Robotics: International Sessions on Robots and Assembly 9 p (SEE N93-15298 04-61) Avail: CASI HC A02/MF A02
The motion capabilities and limitations of ASAE's IRL6 welding robot were studied, including timing of its motion along nine different straight line segments, ranging in length from 10-300 mm. Data collection and analysis were performed automatically by a personal computer linked to the robot. Indirect time and motion study was performed by measuring accelerations at the tool center point. The programmed motion velocities ranged from 100-1100 mm/sec. A model for determining programmed robot velocities and for estimating times of motion, while taking full advantage of the robot's capabilities was developed. The model and the data collected during the measurements were integrated into a database of robot capabilities which was implemented in an off-line task-planning and programming system for robotic welding. Alternative motion paths between seams were evaluated, and motion velocities were assigned to these paths. Similar methodology can be applied to different robots by implementing the established database for automated task planning.

CAD-based off-line programming and sensor signal processing in robotics
93N15299
SIEGLER, ANDRAS; BATHOR, MIKLOS In CASA-RI/SME, Proceedings of the International Conference on CACAM and AMT. Volume 3: IFIP/Robotics: International Sessions on Robots and Assembly 8 p (SEE N93-15298 04-61) Avail: CASI HC A02/MF A02
The first part of the paper describes a three-dimensional computer animation system to be used for creating motion programs for a set of actors. The animation package includes a language for describing spatial motion of bodies as well as an interactive tool to be used for assigning geometrical attributes to them and for guiding and visualizing the play-back of motion programs. One of the main uses of the package is robot programming and motion simulation. A geometrical modeller, which is an aid in creating the models of animated bodies, is also described. The second part of the paper gives an overview on computer vision and force torque measurement and processing units developed for robotics and other automation purposes.

A concept for a supervised autonomous robot
93N14950
KALAYCIOGLU, S. In Canadian Space Agency, Proceedings of the Sixth CASI Conference on Astronautics 17 p (SEE N93-14920 04-12) Previously announced in IAA as A91-34956 Avail: Issuing Activity (Canadian Aeronautics and Space Inst., 222 Somerset St. W., Suite 601, Ottawa, Ontario K2P OJ1 Canada)
The paper describes work in progress at Thomson-CSF Systems Canada Inc. on the Mobile Servicing System (MSS) Autonomous Robotics Program. The main objective of this program is to define and plan the development of technologies required to provide a supervised autonomous operation capability for the Special Purpose Dexterous Manipulator (SPDM) on the Mobile Servicing System (MSS). In this paper, a telerobotics system concept is introduced and a summary of the system requirements is given. The development methodology as well as the concept for a supervised autonomous robot (telerobotics) are briefly explained. The functional and physical architectures of the telerobotics system are also provided. This system will be responsible for carrying out operations such as assembly and maintenance of the Space Station Freedom; loading / unloading from the shuttle; and retrieval and deployment of the shuttle, etc. The paper also investigates an operational scenario for maintenance of the Space Station Freedom and briefly describes the operational scenario for changing an orbital replacement unit (ORU) on the Mobile Servicing System. The functional responsibilities of the system components in order to implement the ORU change are outlined.

A robotic planning system
93N14949
CHRYSTALL, KEITH; DAGNINO, A.; FEIGHAN, P. In Canadian Space Agency, Proceedings of the Sixth CASI Conference on Astronautics 9 p (SEE N93-14920 04-12) Previously announced in IAA as A91-34955 Avail: Issuing Activity (Canadian Aeronautics and Space Inst., 222 Somerset St. W., Suite 601, Ottawa, Ontario K2P OJ1 Canada)
Space station robots are expected to be viable substitutes to astronauts in the execution of space station assembly, repair and maintenance tasks. This paper presents a multi-level robotic planning system for the assembly of electronic components in a printed circuit board, employing surface-mount

technology. The NASNBS Standard Reference Model (NASREM) control architecture was used as a model for this system. The NASREM architecture is hierarchically structured into multiple layers of decreasing complexity and horizontally partitioned into three sections: sensory processing, world modelling, and task decomposition. The approach followed in this project was to develop a knowledge based system to determine the activities and resources required to assemble components in a printed circuit board. Necessary activities are then decomposed into low level actions that can be executed by robotic workcells. By employing this system, robot programming is simplified as assembly tasks may be specified very concisely and all the required robot actions are automatically generated. The technology is adaptable to both space-based and terrestrial robot control systems.

Dynamics and control of a rigid/flexible manipulator
93N14684
YEH, CHUN-TIEN Avail: Univ. Microfilms Order No. DA9229776
Control of high-speed, light-weight robotic manipulators is a challenge because of their special dynamic characteristics. A two-stage control algorithm for the position control of flexible manipulators is proposed. First, the more complex, flexible robot system is replaced by a simplified hypothetical rigid body system (HRRA) with offline trajectory planning. This reduces the complexity of the controller design for the flexible robotic arm. A parameter-optimization approach was adopted to minimize the difference between these two models in this stage. Also, a comparison of computational efficiency is made among the methods of calculus-of-variations, dynamic-programming, and the proposed parameter-optimization. At the second stage, simple linear state feedback controllers, based on the simplified hypothetical rigid body model, are proposed to control the actual robotic system. With the feedback gains selected properly by the pole-placement and linear quadratic methods, the results show satisfactory achievement of the motion objectives. The algorithm is implemented for a two-link rigid/flexible robotic arm, and the results indicate that the procedure is capable of providing effective control with much simpler computational requirements than those of procedures published previously.

Real-time gaze holding in binocular robot vision
93N14582
COOMBS, DAVID J. Avail: CASI HC A08/MF A02
Using a binocular, maneuverable visual system, a robot that holds its gaze on a visual target can enjoy improved visual perception and performance in interacting with the world. This dissertation examines the problem of holding gaze on a moving object from a moving platform, without requiring the ability to recognize the target. A novel aspect of the approach taken is the use of controlled camera movements to simplify the visual processing necessary to keep the cameras locked on the target. A gaze holding system on the Rochester robot's binocular head demonstrates this approach. Even while the robot is moving, the cameras are able to track an object that rotates and moves in three dimensions.

Nonholonomic motion of free-flying space robots
93N13638
MUKHERJEE, RANJAN Avail: Univ. Microfilms Order No. DA9218468
A free-flying space vehicle with one or more manipulators is expected to perform various tasks in space, like the construction of space stations, deployment of large antennas and solar power stations, and the servicing and maintenance of satellites. The kinematics and dynamics of these space robots are significantly different from terrestrial robots. This is because of the nonholonomic nature of the momentum constraints that govern their motion. We describe a 6-DOF space robot by nine state variables: the six joint angles of the manipulator and the three dependent Euler angles describing the orientation of the space vehicle. The nonholonomy in the mechanical structure manifests itself when we show that it is possible to converge all the nine state variables to their desired values by controlling only the six joints of the manipulator. We plan this trajectory using a Liapunov function and by adopting a bi-directional approach. Another interesting feature of free-flying space robots is the presence of a special kind of redundancy in its mechanical structure. This redundancy, which we term as nonholonomic redundancy, exhibits itself only after a global motion and is shown to exist in the absence of ordinary kinematic redundancy. We establish methods to utilize nonholonomic redundancy for avoiding obstacles and joint limits, while planning a trajectory for the end-effector. Finally we discuss the inverse dynamics problem of multibody systems in space. While solving for the inverse dynamics, the computations for the inverse kinematics are considered simultaneously, and both computations are developed on the basis of momentum constraints. This reduces the computational time significantly. We establish an efficient algorithm for the real time computation of the inverse dynamics. We also discuss the scope of parallel recursion for further reduction of the time for computing the inverse dynamics.

Robotic exploration of surfaces and its application to legged locomotion
93N13540
SINHA, PRAMATH RAJ Avail: Univ. Microfilms Order No. DA9212004
Material properties like penetrability, compliance, and surface roughness are important in the characterization of the environment. While concentrating on issues of geometry and shape, researchers in perceptual robotics, until recently, have not quite addressed the issue of the extraction of material properties from the environment. The goal of this

research is to design and implement a robotic system that will actively explore a surface to extract its material characteristics. Further the relevance of material properties in the legged locomotion of robots is also recognized and our research objectives are extended towards building a robotic system for exploration such that is actively perceives material properties during the process of legged locomotion. The chosen approach to the design and implementation of such a robotic system is to first select an appropriate environment model and then to design exploratory procedures salient to each attribute of interest. These exploratory procedures are then implemented through an experimental setup and the results show that material properties can be reliably measured. The design, implementation, and results of a framework for surface exploration to recover material properties are presented. Further, the exploratory procedures for exploration are integrated into an active perceptual scheme for legged locomotion. The perceptual scheme is designed around creating the ability for the robot to sense variations in terrain properties while it is walking, so that it may be able to avoid sinking, slipping, and falling due to unexpected changes in the terrain properties, and make suitable changes in its foot forces to continue locomotion. Finite element simulations of the foot-terrain interaction are used to justify some of the strategies used in this active perceptual scheme. The active perceptual scheme is implemented by simulating a leg-ankle-foot system with a PUMA arm-complaint wrist-foot system and an accelerometer mounted on the foot to detect slip. Details of implementation and experimental results are presented.

The 3-D computer vision techniques for object following and obstacle avoidance
93N13245
EVANS, RICHARD In AGARD, Machine Perception 24 p (SEE N93-13238 03-63) Sponsored in part by Commission of the European Communities Avail: CASI HC A03/MF A03
Imaging sensors are powerful tools enabling remote control, by tele-operation, of numerous tasks where the operator requires an appreciation of the three-dimensional structure of the viewed scene. Passive video sensors also lend themselves to tasks where covert operation or electromagnetic compatibility is required. A commonly mooted tele-operational task is that of driving a known vehicle through an unknown terrain - or keeping station on a known object moving through an unknown terrain. The computer vision aspects of automating this task are divided into two separate vision functions, which are the subjects of this paper: (1) analysis of image sequences of a general scene to extract its three dimensional (3D) structure without any prior information; and (2) analysis of images of a well defined object, to extract its 3D position and orientation relative to the sensor. For both these functions, the paper provides a brief introduction to possible techniques followed by further descriptions of particular systems, DROID and RAPiD, developed by Roke Manor Research Limited. DROID is a general, feature-based 3D vision system using the structure-from-motion principle. That is, it uses the apparent image-plane movement of localized features viewed by a moving sensor to extract the three-dimensional structure of the scene. RAPiD is a model-based real-time tracker which extracts the position (X,Y,Z) and orientation (roll, pitch, yaw) of a known object from image data. The system operates iteratively, using prediction of object pose (position and orientation) to cue the search for selected edge features in subsequent imagery. This approach results in minimal processing of image pixels, so that the system can be implemented at full video rate using modest hardware.

Machine perception exploiting high-level spatio-temporal models
93N13244
DICKMANNS, E. D. In AGARD, Machine Perception 17 p (SEE N93-13238 03-63) Avail: CASI HC A03/MF A03
A paradigm for machine perception is presented which takes time and 3D space in an integrated manner as the underlying framework for internal representation of the sensorially observed outside world. This world is considered to consist of material and mental processes evolving over time. The concept of state and control variables developed in the natural sciences and engineering over the last three centuries is exploited to find a new, more natural access to dynamic real-time vision and intelligence. Schopenhauer's conjecture of 'The world as evolving process and internal representation' (1819) is combined with modern recursive estimation techniques (Kalman 60) and some components from geometry and AI in order to arrive at a very efficient scheme for autonomous robotic agents dealing with evolving processes in the real world in real time. Application to autonomous mobile robots is discussed.

3-D computer vision for navigation/control of mobile robots
93N13243
GARIBOTTO, G. B.; MASCIANGELO, S. In AGARD, Machine Perception 13 p (SEE N93-13238 03-63) Avail: CASI HC A03/MF A03
The aim of this lecture is to investigate how much visual sensors may be effective in supporting autonomous navigation of mobile robots. Although in practical realizations, with robustness and reliability constraints, it is always necessary to integrate multisensor modalities, the discussion here is limited to an analysis of computer vision advantages and disadvantages, with particular attention given to: (1) a binocular stereo vision module for obstacle detection, with no precise calibration (réactive process to operate at a fast rate, from 5 to 10 Hz); trinocular stereovision based on segment primitives for the reconstruction of free space for navigation, in which case an acccurate calibration procedure is requested;

and landmark detection for self-positioning and orientation of a mobile vehicle, using perspective invariants, for indoor navigation. Some comments are also provided on computer vision architectures to support real time implementations. A real-time front end vision subsystem is described, which is able to compute 3D segment based stereovision at 5 Hz and segment token tracking at 10 Hz. Finally, some demo arrangements are briefly discussed where an intense experimentation of such results is in progress, as a test bed for different industrial applications.

Machine Perception
93N13238 Lecture series held in Hamton, VA, 3-4 Sep. 1992, in Neubiberg, Germany, 14-15 Sep. 1992, and in Madrid, Spain, 17-18 Sep. 1992
Avail: CASI HC A10/MF A03

Space Station robotics planning tools
93N11975
TESTA, BRIDGET MINTZ In NASA. Lyndon B. Johnson Space Center, Fifth Annual Workshop on Space Operations Applications and Research (SOAR 1991), Volume 1 p 382-390 (SEE N93-11921 02-59) Avail: CASI HC A02/MF A04
The concepts are described for the set of advanced Space Station Freedom (SSF) robotics planning tools for use in the Space Station Control Center (SSCC). It is also shown how planning for SSF robotics operations is an international process, and baseline concepts are indicated for that process. Current SRMS methods provide the backdrop for this SSF theater of multiple robots, long operating time-space, advanced tools, and international cooperation.

Remote systems development
93N11971
OLSEN, R.; SCHAEFER, O.; HUSSEY, J. In NASA. Lyndon B. Johnson Space Center, Fifth Annual Workshop on Space Operations Applications and Research (SOAR 1991), Volume 1 p 331-347 (SEE N93-11921 02-59) Avail: CASI HC A03/MF A04
Potential space missions of the nineties and the next century require that we look at the broad category of remote systems as an important means to achieve cost-effective operations, exploration and colonization objectives. This paper addresses such missions, which can use remote systems technology as the basis for identifying required capabilities which must be provided. The relationship of the space-based tasks to similar tasks required for terrestrial applications is discussed. The development status of the required technology is assessed and major issues which must be addressed to meet future requirements are identified. This includes the proper mix of humans and machines, from pure teleoperation to full autonomy; the degree of worksite compatibility for a robotic system; and the required design parameters, such as degrees-of-freedom. Methods for resolution are discussed including analysis, graphical simulation and the use of laboratory test beds. Grumman experience in the application of these techniques to a variety of design issues are presented utilizing the Telerobotics Development Laboratory which includes a 17-DOF robot system, a variety of sensing elements, Deneb/IRIS graphics workstations and control stations. The use of task/worksite mockups, remote system development test beds and graphical analysis are discussed with examples of typical results such as estimates of task times, task feasibility and resulting recommendations for design changes. The relationship of this experience and lessons-learned to future development of remote systems is also discussed.

Exoskeleton master controller with force-reflecting telepresence
93N11970
BURKE, JAMES B.; BARTHOLET, STEPHEN J.; NELSON, DAVID K. (Aerospace Medical Research Labs., Wright-Patterson AFB, OH.) In NASA. Lyndon B. Johnson Space Center, Fifth Annual Workshop on Space Operations Applications and Research (SOAR 1991), Volume 1 p 321-330 (SEE N93-11921 02-59) Avail: CASI HC A02/MF A04
A thorough understanding of the requirements for successful master-slave robotic systems is becoming increasingly desirable. Such systems can aid in the accomplishment of tasks that are hazardous or inaccessible to humans. Although a history of use has proven master-slave systems to be viable, system requirements and the impact of specifications on the human factors side of system performance are not well known. In support of the next phase of teleoperation research being conducted at the Armstrong Research Laboratory, a force-reflecting, seven degree of freedom exoskeleton for master-slave teleoperation has been concepted, and is presently being developed. The exoskeleton has a unique kinematic structure that complements the structure of the human arm. It provides a natural means for teleoperating a dexterous, possibly redundant manipulator. It allows ease of use without operator fatigue and faithfully follows human arm and wrist motions. Reflected forces and moments are remotely transmitted to the operator hand grip using a cable transmission scheme. This paper presents the exoskeleton concept and development results to date. Conceptual design, hardware, algorithms, computer architecture, and software are covered.

The development of system components to provide proprioceptive and tactile information to the human for future telepresence systems
93N11968
WRIGHT, AMMON K. In NASA. Lyndon B. Johnson Space Center, Fifth Annual Workshop on Space Operations Applications and Research (SOAR 1991), Volume 1 p 311 (SEE N93-11921 02-59)
Avail: CASI HC A01/MF A04
System components are presented that are being implemented to augment teleoperated systems by

providing both force and tactile information to the human operator. The concept proposed is the control of a manipulator to perform tasks; i.e., flight line maintenance and repair of combat aircraft or satellites while under the control of a human operator at a remote location to maintain mission effectiveness in a hostile environment. The human would control the motion of the manipulator via a master system with information from the remote site being fed back by direct stimulation of the humans sensory mechanisms or by graphic interpretation of displays. We are interested in providing the operator feedback of position, force, auditory, vision, and tactile information to aide in the human's cognitive ability to control the manipulator. This sensory information from the remote site would then be presented to the operator in such a manner as to enhance his performance while providing him a sense of being present at the remote location, this is known as telepresence. Also discussed is the research done by the Human Sensory Feedback (HSF) facility at the Armstrong Laboratory to provide tactile and proprioceptive feedback to the operator. The system components of this system includes tactile sensor and stimulators, dexterous robotic hands, and the control of positioning and operating industrial robots with exoskeletal mechanisms.

Effects of spatially displaced feedback on remote manipulation tasks
93N11966
MANAHAN, MEERA K.; STUART, MARK A.; BIERSCHWALE, JOHN M.; HWANG, ELLEN Y.; LEGENDRE, A. J. (Lockheed Engineering and Sciences Co., Houston, TX.); (Lockheed Engineering and Sciences Co., Houston, TX.); (Lockheed Engineering and Sciences Co., Houston, TX.); (Lockheed Engineering and Sciences Co., Houston, TX.) In its Fifth Annual Workshop on Space Operations Applications and Research (SOAR 1991), Volume 1 p 302-309 (SEE N93-11921 02-59) Avail: CASI HC A02/MF A04
Several studies have been performed to determine the effects on computer and direct manipulation task performance when viewing conditions are spatially displaced. Whether results from these studies can be directly applied to remote manipulation tasks is quenstionable. The objective of this evaluation was to determine the effects of reversed, inverted, and inverted/reversed views on remote manipulation task performance using two 3-Degree of Freedom (DOF) hand controllers and a replica position hand controller. Results showed that trials using the inverted viewing condition showed the worst performance, followed by the inverted/reversed view and the reversed view when using the 2x3 DOF. However, these differences were not significant. The inverted and inverted/reversed viewing conditions were significantly worse than the normal and reversed viewing conditions when using the Kraft Replica. A second evaluation was conducted in which additional trials were performed with each viewing condition to determine the long term effects of spatially displaced views on task performance for the hand controllers. Results of the second evaluation indicated that there was more of a difference in performance between the perturbed viewing conditions and the normal viewing condition with the Kraft Replica than with the 2x3 DOF.

A neuro-collision avoidance strategy for robot manipulators
93N11962
ONEMA, JOEL P.; MACLAUNCHLAN, ROBERT A. In NASA. Lyndon B. Johnson Space Center, Fifth Annual Workshop on Space Operations Applications and Research (SOAR 1991), Volume 1 p 272-279 (SEE N93-11921 02-59) Avail: CASI HC A02/MF A04
The area of collision avoidance and path planning in robotics has received much attention in the research community. Our study centers on a combination of an artificial neural network paradigm with a motion planning strategy that insures safe motion of the Articulated Two-Link Arm with Scissor Hand System relative to an object. Whenever an obstacle is encountered, the arm attempts to slide along the obstacle surface, thereby avoiding collision by means of the local tangent strategy and its artificial neural network implementation. This combination compensates the inverse kinematics of a robot manipulator. Simulation results indicate that a neuro-collision avoidance strategy can be achieved by means of a learning local tangent method.

A new scheme of force reflecting control
93N11960
KIM, WON S. In NASA. Lyndon B. Johnson Space Center, Fifth Annual Workshop on Space Operations Applications and Research (SOAR 1991), Volume 1 p 254-261 (SEE N93-11921 02-59) Sponsored by NASA, Washington Avail: CASI HC A02/MF A04
A new scheme of force reflecting control has been developed that incorporates position-error-based force reflection and robot compliance control. The operator is provided with a kinesthetic force feedback which is proportional to the position error between the operator-commanded and the actual position of the robot arm. Robot compliance control, which increases the effective compliance of the robot, is implemented by low pass filtering the outputs of the force/torque sensor mounted on the base of robot hand and using these signals to alter the operator's position command. This position-error-based force reflection scheme combined with shared compliance control has been implemented successfully to the Advanced Teleoperation system consisting of dissimilar master-slave arms. Stability measurements have demonstrated unprecedentedly high force reflection gains of up to 2 or 3, even though the slave arm is much stiffer than operator's hand holding the force reflecting hand controller. Peg-in-hole experiments were performed with eight different operating modes to evaluate the new

force-reflecting control scheme. Best task performance resulted with this new control scheme.

Fuzzy logic control of telerobot manipulators
93N11959
FRANKE, ERNEST A.; NEDUNGADI, ASHOK In NASA. Lyndon B. Johnson Space Center, Fifth Annual Workshop on Space Operations Applications and Research (SOAR 1991), Volume 1 p 248-253 (SEE N93-11921 02-59) Avail: CASI HC A02/MF A04
Telerobot systems for advanced applications will require manipulators with redundant 'degrees of freedom' (DOF) that are capable of adapting manipulator configurations to avoid obstacles while achieving the user specified goal. Conventional methods for control of manipulators (based on solution of the inverse kinematics) cannot be easily extended to these situations. Fuzzy logic control offers a possible solution to these needs. A current research program at SRI developed a fuzzy logic controller for a redundant, 4 DOF, planar manipulator. The manipulator end point trajectory can be specified by either a computer program (robot mode) or by manual input (teleoperator). The approach used expresses end-point error and the location of manipulator joints as fuzzy variables. Joint motions are determined by a fuzzy rule set without requiring solution of the inverse kinematics. Additional rules for sensor data, obstacle avoidance and preferred manipulator configuration, e.g., 'righty' or 'lefty', are easily accommodated. The procedure used to generate the fuzzy rules can be extended to higher DOF systems.

Contact detection and contact motion for error recovery in the presence of uncertainties
93N11956
XIAO, JING In NASA. Lyndon B. Johnson Space Center, Fifth Annual Workshop on Space Operations Applications and Research (SOAR 1991), Volume 1 p 230-237 (SEE N93-11921 02-59) Avail: CASI HC A02/MF A04
Due to various kinds of uncertainties, a robot motion may fail and result in some unintended contact between the object held by the robot and the environment, which greatly hampers robotics applications on tasks with high-precision requirements, such as assembly tasks. Aiming at automatically recovering a robotic task from such a failure, this paper discusses, in the presence of uncertainties, contact detection based on contact motion for recovery. It presents a framework for on-line recognizing contacts using multiple sensor modalities in the presence of sensing uncertainties and means for ensuring successful compliant motions in the presence of sensing and control uncertainties.

Requirements and applications for robotic servicing of military space systems
93N11953
LEDFORD, OTTO C., JR.; BENNETT, RODNEY G. (Air Force Space Div., El Segundo, CA.) In NASA. Lyndon B. Johnson Space Center, Fifth Annual Workshop on Space Operations Applications and Research (SOAR 1991), Volume 1 p 206-212 (SEE N93-11921 02-59) Avail: CASI HC A02/MF A04
The utility of on-orbit servicing of spacecraft has been demonstrated by NASA several times using shuttle-based astronaut EVA. There has been interest in utilizing on-orbit servicing for military space systems as well. This interest has been driven by the increasing reliance of all branches of the military upon space-based assets, the growing numbers, complexity, and cost of those assets, and a desire to normalize support policies for space-based operations. Many military satellites are placed in orbits which are unduly hostile for astronaut operations and/or cannot be reached by the shuttle. In addition, some of the projected tasks may involve hazardous operations. This has led to a focus on robotic systems, instead of astronauts, for the basis of projected servicing systems. This paper describes studies and activities which will hopefully lead to on-orbit servicing being one of the tools available to military space systems designers and operators. The utility of various forms of servicing has been evaluated for present and projected systems, critical technologies have been identified, and strategies for the development and insertion of this technology into operational systems have been developed. Many of the projected plans have been adversely affected by budgetary restrictions and evolving architectures, but the fundamental benefits and requirements are well understood. A method of introducing servicing capabilities in a manner which has a low impact on the system designer and does not require the prior development of an expensive infrastructure is discussed. This can potentially lead to an evolutionary implementation of the full technology.

Integration of task level planning and diagnosis for an intelligent robot
93N11929
CHAN, AMY W. In NASA. Lyndon B. Johnson Space Center, Fifth Annual Workshop on Space Operations Applications and Research (SOAR 1991), Volume 1 p 52-59 (SEE N93-11921 02-59) Avail: CASI HC A02/MF A04
A satellite floating space is diagnosed with a telerobot attached performing maintenance or replacement tasks. This research included three objectives. The first objective was to generate intelligent path planning for a robot to move around a satellite. The second objective was to diagnose possible faulty scenarios in the satellite. The third objective included two tasks. The first task was to combine intelligent path planning with diagnosis. The second task was to build an interface between the combined intelligent system with Robosim. The ability of a robot to deal with unexpected scenarios is particularly important in space since the situation could be different from time to time so that the telerobot must be capable of detecting that the situation has changed and the necessity may exist to

alter its behavior based on the new situation. The feature of allowing human-in-the-loop is also very important in space. In some extreme cases, the situation is beyond the capability of a robot so our research project allows the human to override the decision of a robot.

ALECSYS and the AutonoMouse: Learning to control a real robot by distributed classifier systems
93N11227
DORIGO, MARCO Avail: Politecnico di Milano, Piazza Leonardo da Vinci 32, 20133 Milan, Italy
ALECSYS (A LEarning Classifier SYStem), is a parallel distributed learning classifier system that provides the learning system designer with two basic tools. The first tool, low level parallelism, allows him to use the desired computational power by parallelization of a single learning Classifier System (CS); the second tool, high level parallelism, gives him the possibility to connect, with great flexibility, many cooperating CS's. AutonoMouse, a little autonomous robot, shaped like a mouse, that gives ALECSYS a body, is discussed. The design of autonomous mouse sized robots (AutonoMouses) with the capacity of surviving in a real environment is focused upon. The overall goal is very ambitious and cannot be solved by any existing computational paradigm. Results obtained using ALECSYS as learning software, the transputer as computing hardware, and a home made AutonoMouse as robot, are reported. ALECSYS is illustrated and experiments, both in a simulated environment and in the real world, are reported.

Selective perception for robot driving
93N10749
REECE, DOUGLAS A. Avail: CASI HC A10/ MF A03
Robots performing complex tasks in rich environments need very good perception modules in order to understand their situation and choose the best action. Robot planning systems have typically assumed that perception was so good that it could refresh the entire world model whenever the planning system needed it, or whenever anything in the world changed. Unfortunately, this assumption is completely unrealistic in many real-world domains because perception is far too difficult. Robots in these domains cannot use the traditional planner paradigm, but instead need a new system design that integrates reasoning with perception. In this thesis I describe how reasoning can be integrated with perception, how task knowledge can be used to select perceptual targets, and how this selection dramatically reduces the computational cost of perception. The domain addressed in this thesis is driving in traffic. I have developed a microscopic traffic simulator called PHAROS that defines the street environment for this research. PHAROS contains detailed representations of streets, markings, signs, signals, and cars. It can simulate perception and implement commands for a vehicle controlled by a separate program. I have also developed a computational model of driving called Ulysses that defines the driving task. The model describes how various traffic objects in the world determine what actions that a robot must take.

Optimal robot trajectory planning
93N10570
BUCHAL, R. O. In Carleton Univ., Proceedings of the Twelfth Canadian Congress of Applied Mechanics, Volumes 1 and 2 p 858-859 (SEE N93-10466 01-31) Avail: Issuing Activity (Canadian Society for Mechanical Engineering, 2050 Mansfield St., Suite 700, Montreal, Quebec H3A 1Z7 Canada)
In order to achieve the objectives of off-line robot programming and automatic program synthesis, an effective trajectory planning method is required. A method is presented for determining optimal robot trajectories subject to the constraints of collision avoidance, joint displacement limits, and joint actuator force limits. The constraints are represented by penalty functions, and a discrete gradient approach is used to optimize the equivalent unconstrained objective functional. The model includes the dynamic equations of motion, which were generated for the planar four-link manipulator using the MACSYMA symbolic algebra package. In the current implementation, the user interactively specifies a number of different starting trajectories so that several alternative locally optimal trajectories are generated.

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14. Abstract

To ensure the capability of defence, a demand for equipment and systems which can be embraced under the title of "Robotics" will emerge in the near future. In this context, "Robotics" represents a specific problem area involving all the guidance and control functions which are associated with achieving goal-oriented autonomous behaviour in structured and unstructured environments for mobile and manipulator systems as applied to ground, sea, air and space operations. Related robotic systems must combine constituent functions such as intelligent decision making, control, manipulation, motion, sensing and communication.

The scope of the special course will cover new developments in the areas of autonomous navigation for planetary and surface systems, and control and operations of remote manipulators.

Topics to be covered include:

- Kinematics, dynamics and mobility;
- Sensing (vision, tactile, acoustic, etc.) and sensory processing;
- Sensory interactive task decomposition, planning and problem solving;
- World modelling;
- Programming techniques and learning, cognitive control, adaptive sensory-motor control;
- System integration, test and evaluation;
- Man-machine interfaces.

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